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The Business Prospect of Biomass to Methanol Development in Namibia: A Review

La perspectiva empresarial del desarrollo de biomasa a metanol en Namibia: una revisión

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ABSTRACT

In Indonesia, the demand for methanol as renewable alternatives or chemical feedstock has been rising significantly to address the shortage of its domestic fossil fuels need. In the future, Indonesia expects to increase their methanol production using gasification process to balance its domestic demand. This paper presents the business prospect of methanol production from overseas, i.e., Namibia using biomass (encroacher bush types) feedstocks. It is concluded that biomass is available as an alternative feedstock to generate pure methanol. In Namibia, biomass is one of the most abundant and easily accessed resources for energy uses. However, without appropriate business endorsement by the government, such as a well-designed policies and incentives, the project's prospect is still limited and very costly to be implemented. The financial planning of investment, particularly in how to find the best technological design of methanol processing, is highly essential to gain the maximum net business profit.

Keywords: methanol production, energy demand, biomass feedstock, biomass pre-treatment and gasification and synthesis gas.

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RESUMEN

En Indonesia, la demanda de metanol como alternativa renovable o materia prima química ha aumentado considerablemente para hacer frente a la escasez de combustibles fósiles nacionales. En el futuro, Indonesia espera aumentar su producción de metanol utilizando el proceso de gasificación para equilibrar su demanda interna. Este artículo presenta las perspectivas de negocio de la producción de metanol desde el extranjero, es decir, Namibia utilizando biomasa (tipos de arbustos invasores) como materia prima. Se concluye que la biomasa está disponible como materia prima alternativa para generar metanol puro. En Namibia, la biomasa es uno de los recursos más abundantes y de fácil acceso para usos energéticos. Sin embargo, sin el apoyo empresarial apropiado del gobierno, como políticas e incentivos bien diseñados, las perspectivas del proyecto siguen siendo limitadas y muy costosas de implementar. La planificación financiera de la inversión, particularmente en cómo encontrar el mejor diseño tecnológico de procesamiento de metanol, es altamente esencial para obtener el máximo beneficio neto del negocio.

Palabras clave: producción de metanol, demanda de energía, materia prima de biomasa, pretratamiento de biomasa y gasificación y gas de síntesis.

1. Introduction

The increasing demand of clean energy sources globally is the key objective for industrial sectors today to adopt environmentally safe and small operational cost type of technology. In Indonesia, methanol has been currently considered either as renewable alternatives or chemical feedstock to address the shortage of fossil fuels and to reduce greenhouse gas emissions without adversely affecting the food supply chain. To meet this objective, biomass resources, especially those of unused or wild plants, are in the spotlight.

With the booming production of renewable fuels in transportation sector, the steadily growing demand for methanol shows no signs of declining trend (Pérez-Fortes, et al., 2016). The Ministry of Industry of Republic Indonesia (2020) stated that methanol demand in Indonesia has reached 1.1 million ton in year 2019. However, until date, its annual domestic production capacity reaches only about 660,000 ton produced by a single industry that is Kaltim Methanol company. In the future strategy, Indonesia is planning to increase its methanol supply with capacity 1.8 million ton per year which generated from 4.7 to 6.1 million ton of coal using gasification process of technology. By looking at the soaring trend of Indonesian methanol demand in the future, therefore, it is important to improve its supply to balance their market.

Methanol has a long proud history since ancient times, i.e., when the Egyptians produced methanol from wood and utilized it to preserve mummies (Vertes, et al., 2010). However, there was no significant improvement in its production process until the twentieth century. In early 1920s, methanol was used for racing fuel as a blending component with benzene to generate maximum performance from a given engine swept volume (SGS Inspire Team, 2020). In 1923, methanol was first commercially produced by *Badische Anilin and Soda Fabrik* (BASF) in Germany (Howarda & Bethiana, 2020). The synthesis processing adopted in this BASF was both high pressure (250-350 bar) and high temperature between 320 ˚C and 450 ˚C combined with catalyst based of Zn that contained ZnO/Cr_2O_3 (Howarda & Bethiana, 2020). The processing technology was then improved in year 1960s of which ICI Synetix (now Johnson Matthey) adopted Cu-Zn catalyst to convert syngas into methanol at both low pressure of 50-100 atm and low temperature between 200 ˚C-300 ˚C (Olah, Goeppert & Prakash, 2009). Since then, this low pressurized technology has become the reference mostly on the existing type of technologies today; while the previous one was abandoned because it was not economically profited.

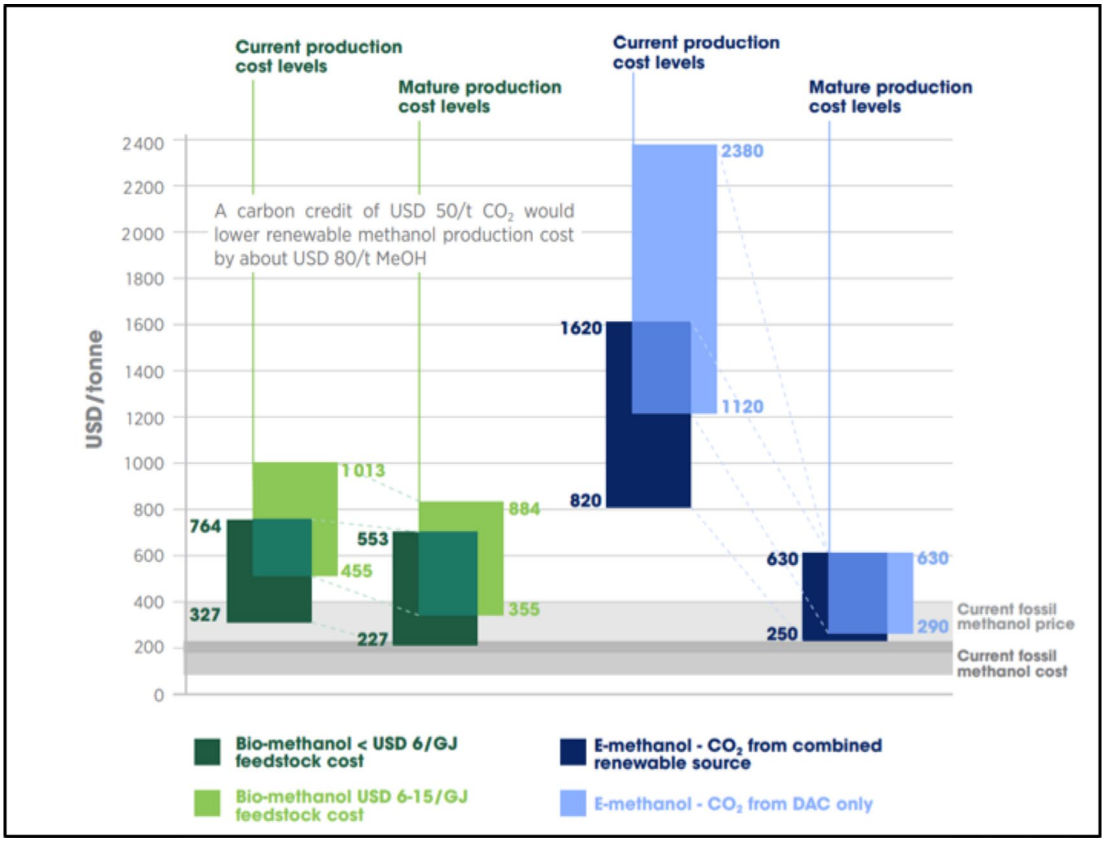
Methanol can be either produced from i) fossil fuels, ii) renewable feedstocks or iii) green e-methanol using CO_2 captured from renewable sources. Methanol structure from fossil sources is identical to that of renewable sources. Thus, the latter can be utilized as a feed stock to produce various products such as chemicals, materials, plastics and products, and as a fuel for transport shipping, cooking, heating and electricity production. Methanol's use as a fuel – either by itself as a blend with gasoline, for the production of biodiesel, or in the form of methyl tert-butyl ether (MTBE) and dimethyl ether (DME)– has increased rapidly since the mid-2000s (International Renewable Energy Agency IRENA, 2021).

According IRENA (2021), methanol production currently has nearly doubled since the past decade where the largest shares are supplied from China through coal-based methanol. In year 2019, global methanol demand reached nearly 100 million tons where the largest shares are applied for gasoline blending in transportation fuel (14 %). Figure 1 presents the uses of methanol globally in year 2019. In the future, methanol demand is expected to increase by more than 120 million tons in year 2025 (Methanol Market Services Asia MMSA, 2021 & Berggren, 2019). Under current trends, IRENA predicts that methanol production could increase to 500 million ton per year by 2050.

Compared to fossil-based methanol, the production cost of renewable-based methanol is currently more expensive which is ranged from US$ 100 to 250 per ton. Nevertheless, by selecting the lowest cost of biomass feedstocks as well as improvement in the technology processes, methanol production cost could be levelized identically with fossil-based methanol production cost as illustrated in figure 1 (IRENA, 2020).

Figure 1

Current and Future Production Costs of Bio- and E-Methanol

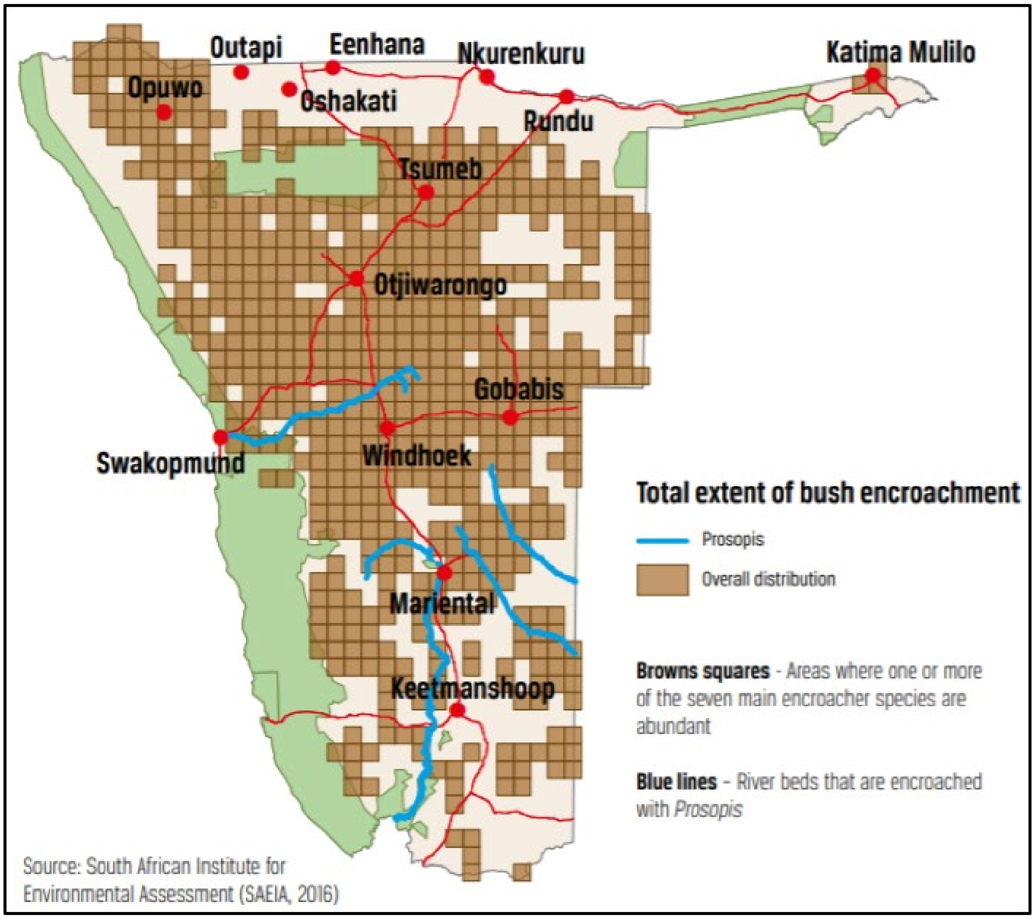


Note: MeOH = methanol. Current fossil-based methanol cost and prices are accounted from coal and natural gas feedstock in 2020. Source: IRENA (2021).

Biomass is one of the most abundant and easily accessed natural resources for energy uses; however, most of these are not fully utilized since they are wildly scattered and often left unused (Ries, 2017). Unused biomass can release large quantities of greenhouse gas emission which can generate adverse impact on environment (Ries, 2017). In Namibia, the biomass abundance of bush encroachment remains a major agricultural problem. It covers about 45 million hectares of Namibia's savannas which could significantly cause a negative effect on livestock productivity significantly. Figure 3 shows the total extent of bush encroachment in Namibia. Approximately 55 % of Namibia's land is bush encroached (South Africa Institute for Environmental Assessment SAIEA, 2016). Several species of dominant bush encroachment in Namibia, among others, are Acacia, Dichrostachs Cinerea, Terminalia Sericea, Mopane, Rhigozum Trichotomum, and Prosopis trees (table 1).

Figure 2

Total Extent of Bush Encroachment in Namibia



Browns squares - Areas where one or more of the seven main encroacher species are abundant

Blue lines - River beds that are encroached with *Prosopis*

Source: South African Institute for Environmental Assessment (SAEIA, 2016)

Table 1

Ranking order of the main bush encroacher species in Namibia Based on a national density basis

Ranking	Scientific Name	English Name	Afrikaans Name	Coverage (%)
1.	Acacia Mellifera	Black-thorn Acacia	Swarthaak/Hakkiesbos	45 %
2.	Colophospermum Mopane	Mopane	Baster Mopane	20 %
3.	Dichrostachys Cinerea	Sickle-Bush	Sekelbos/Papierwiel	14 %
4.	Acacia Reficiens	Red-Thorn	Rooihaak	9 %
5.	Terminalia Sericea	Silver Cluster-Leaf	Vaalbos/Geelhout	8 %
6.	Terminalia Prunioides	Purple-Pot Terminalia	Deurmekaarbos	4 %

Source: De Klerk (2004).

The development of biomass industry in Namibia from encroacher bush feedstocks has been continuously improved (Arteaga-Pérez, et al., 2016). In year 2018, Namibia Power Corporation (NamPower) initiated the first 40 MWe Otjikoto biomass power generation. The main purpose of this biomass power plant development is to achieve Namibia's energy security, affordability and environmental sustainability. Technically, the proposed 40 MWe biomass plant requires approximately 245,000 tons of wood chips (on a dry basis) per year in 85 % capacity factor (Petrick, 2020).

Furthermore, biomass resources can also be used to produce methanol. However, before applying the methanol business, a well-designed of financial model of the project is important. Methanol production cost generally depends on the feedstock cost, investment cost and the efficiency of the conversion technology (IRENA, 2021). According to IEA Bioenergy (2007), the total cost of methanol from biomass based via gasification and subsequent syngas processing, in short and long terms, is within the range of 6 to 15 €/GJ fuel. IRENA (2021) suggests the biomass feedstock cost may vary between US$ 0 and US$ 17/GJ depending on the feedstock types. While, the expected energy efficiency, in terms of High Heating Value (HHV) is about 55 % (fuel-based only); or 48 % (fuel) and 12 % (power). Table 2 presents some examples of energy crops based on their annual growth rate and HHV.

Table 2

The energy content from some biomass feedstocks

Type of Biomass	Annual Growth Rate (dry ton/ha year)	HHV (MJ/kg dry)	Reference
Miscanthus	13 – 30	18.5	Mckendry (2002)
SRC willow	10 – 15	18.7	Mckendry (2002)
Sorghum	0.2 – 19		Klass (1998)
Switchgrass	2.9 – 14	17.4	Mckendry (2002)
Alfalfa	1.6 – 17.4		Klass (1998)
Canary grass	2.7 – 10.8		Klass (1998)
Kenaf Hybrid poplar	10		Drapco, et al (2008)

Source: Basu (2013)

The projected unit cost of biomass ($/GJ) can be measured from the ratio between the unit cost to harvest the biomass ($/dry ton) and HHV (GJ/ dry ton). While the unit methanol cost derived is obtained from the ratio between the cost of biomass and the efficiency of energy conversion technology (Basu, 2013). If a feedstock cost is up to US$ 6/GJ, the cost of renewable methanol expectedly is between US$ 320/ton and US$ 770/ton. The range is highly influenced by the CAPEX, OPEX, and the conversion efficiency of the project (IRENA, 2021). By improving the processing technology, the cost range of renewable methanol could be reduced between US$ 220/ ton and US$ 560/ ton at the same unit cost of the feedstock.

This paper aims to review the variety of processes to produce methanol from biomass resources. By investigating at its step-by-step processing in both technical and economic perspectives, one can obtain the most suited financial strategy to develop the biomass-to-methanol project. In the next section, this paper describes briefly about biomass to methanol production and utilization, including references related to the processing strategies of biomass to methanol production. Section 3 presents the overview of methanol production. Finally, Section 4 reviews the issues related to the methanol supply-chain management and as well as providing recommendation on how to overcome this concern.

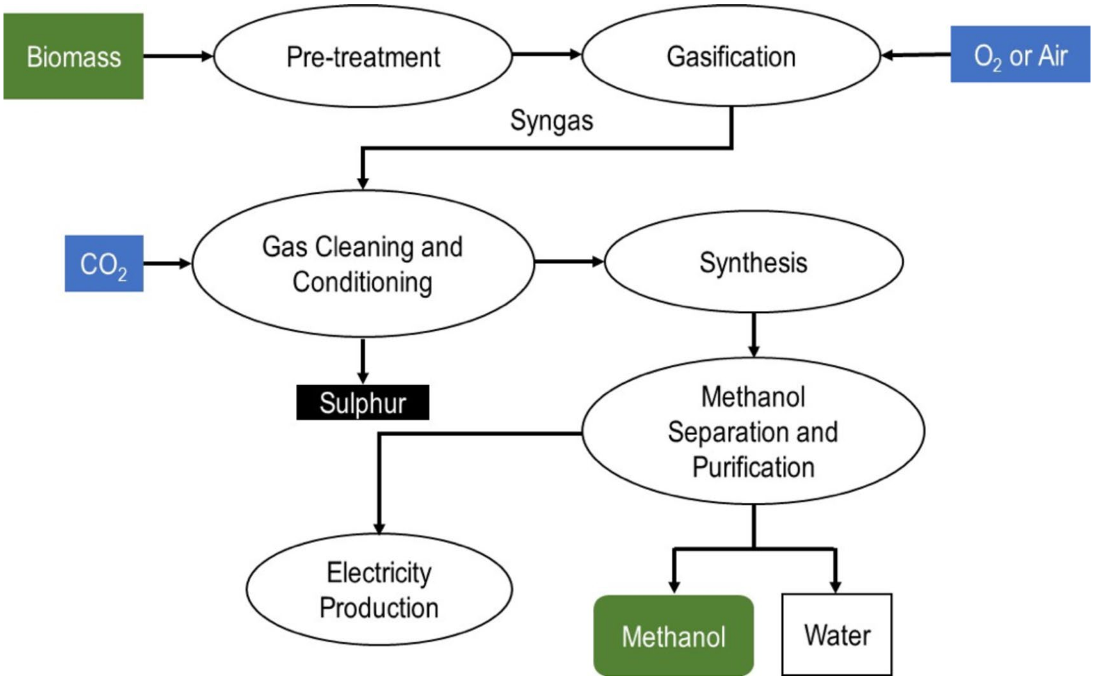
2. Biomass to methanol production and utilization

Vertes et al. (2010) stated that biomass feedstock can be converted into methanol through several production pathways such as: i) biochemical conversion; ii) thermochemical process; iii) pyrolysis; and iv) gasification. The latter has been commonly adopted as it generates methanol in greater yields. In the future, biomass gasification for methanol production may become the most promising technology because it enables a tremendous flexibility between the feedstock and the fuels produced (Dahlquist, 2003).

The process flow of biomass to methanol production is briefly presented in figure 3.

Figure 3

A simplified process flow of biomass to methanol production



Source: Clausen (2011)

The process of biomass to methanol given in figure 4 is briefly described as follows. The raw solid biomass is firstly pre-treated through physical, chemical, or biological pre-treatment. This pre-treated biomass will then enter the gasification process to convert the biomass into a so called "synthesis gas" or "syngas". According to Clausen (2011), the gasification process is related with pyrolysis, partial oxidation (Eq. 1), and gasification reactions (Eq. 2 and 3). In the pyrolysis, the pre-treated solid biomass will be decomposed into volatile gases (i.e., H_2, CO, CO_2, H_2O, CH_4 and higher hydrocarbons, and tars) and solid coke (mainly carbon).

Oxidation of coke:

$$C + {}^{1}/_{2}O_2 \rightarrow CO \qquad (1)$$

Gasification reactions:

$$C + H_2O \rightarrow CO + H_2 \qquad (2)$$

$$C + CO_2 \rightarrow 2CO \qquad (3)$$

The syngas produced from the gasifier is purified from that of sulphur content – due to its poisonous effect on the catalyst used for methanol synthesis. To optimize the methanol synthesis, the syngas is conditioned to balance the H_2 to CO ratio through the water gas shift reaction (Eq. 4). The optimal H_2 to CO ratio is 2 which is expressed in Eq. 5 (Clausen, 2011).

Water Gas Shift (WGS) reaction:

$$H_2O + CO \leftrightarrow CO_2 + H_2 \qquad (4)$$

Methanol synthesis reaction:

$$4H_2O + 2CO \leftrightarrow 2CH_3OH \qquad (5)$$

In addition, the syngas conditioning also includes the CO_2 removal since it delays the chemical reactions during the methanol production and enables the use of smaller downstream equipment which reduces the production cost.

Finally, the methanol synthesis is performed in the catalytic reactor at high pressure and temperature. The gas product from the reactor is cooled to condense the methanol into a liquid form. The liquid methanol will flow into fractional distillation for purification from gasses, water and by-products. In the other hand, the unconverted syngas can be utilized as fuel in gas engine or gas turbine for power generation.

2.1. Biomass pre-treatment and gasification

2.1.1. Biomass pre-treatment

To produce a good syngas quality, a pre-treatment stage of the biomass feedstock is needed. The pre-treatment process aims to break down the lignin and hemicellulose structure as well as disrupting the crystalline structure of cellulose such that the acids or enzymes can easily hydrolyse the cellulose (Kumar et al., 2009). In this stage, the feedstocks are also being purified from the unwanted particles in the downstream processes (IRENA, 2021). Table 3 shows some of the other unwanted compounds which are needed to be removed as well as how to manage their purification. An inert gas might be required to ensure the feed system work properly and safely. Minimizing the flow of this inert gas is essential to reduce the investment cost for overall syngas system and for efficiency of the plant.

Biomass pre-treatment methods can be divided into three general categories: physical, chemical, and biological pre-treatment. The first two pre-treatments are the most widely methods to be employed due to their low cost and user-friendliness (Noorshamsiana et al., 2017; Hosseini Koupaie et al., 2019). However[3], due to the increasing demand of environmentally technology requirement, researchers have started to shift towards biological pre-treatment methods to achieve less energy consumption, improved productivity, the uses of non-toxic components, as well as greater specificity (Arora, et al., 2019; Tsegaye, Balomajumder & Roy, 2019).

Table 3

Examples of the feedstock compounds and cleaning processes

Type of impurities to be removed	Process	More (M) or less (L) common
Particles	Particulate filter	M
Tar and methane	Reform for tar and / or methane decomposition	M
Carbonyl Sulphide (COS)	COS hydrolysis converting COS to H_2S	L
Chlorine and fluorine components	HCL and HF removal	L
Sulphur components	AGR process either with CO_2 removal or separately	M
CO_2	AGR process either with H_2S removal or separately	M

Source: IRENA, 2021

An example of physical pre-treatment, i.e., the size reduction of about 1.5 mm particle size through chipping, grinding, and milling; and then drying process (Yadav et al., 2020). Diyanilla et al. (2020) suggested that physical treatment also includes that of pyrolysis and hydrothermal treatment. This pre-treatment is preferably implemented since the biomass feedstocks for renewable methanol are mostly solid in nature and therefore, they are needed to be homogenised in some particular processes before entering the gasification (IRENA, 2021).

Pyrolysis is another example of physical pre-treatment in which it decomposes the cellulose rapidly into gaseous products and residual char at temperature greater than 300 ˚C (Kumar et al., 2009). Torrefaction can also be another alternative for chemical pre-treatment. According to Basu (2010), torrefaction –a process different from carbonization – is a light pyrolysis process in a temperature range between 230 and 300 ˚C with non-oxygen environment. Basu (2010)

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1 These are referred to that of palm oil biomass based.

stated that torrefaction improves the biomass quality, i.e., increasing its energy density, reducing its oxygen-to-carbon ratio (O/C), and reducing its hygroscopic nature. This is because during the process of torrefaction, the biomass dries (is removed) and partially devolatilizes (is removed), thus reducing its mass while largely preserving the energy content. Compared to the original feedstock, torrefied biomass performs better beause it has lower oxygen and higher carbon content relatively. During the gasification, torrefied biomass prevents the over-oxidation, hence reduces the thermodynamic losses. Kumar et al. (2009) stated that torrefaction method is more effective than that of pyrolysis method.

Chemical pre-treatment is those processes which are related to acid, alkali and organic solvent and ozonolysis treatment (Diyanilla et al., 2020; Kumar et al., 2009). Acid pre-treatment is associated to breaking down mechanism of glucoside bonds between hemicellulose and cellulose chains into sugar monomers (Lloyd & Wyman, 2005). In the process, both inorganic and organic acids are often employed (Kärcher et al., 2015; Nair et al., 2015; Kim et al., 2015; Zu et al., 2014; Du et al., 2016; Jung et al., 2015; Jeong & Lee, 2016). The acid can be applied either as concentrated acids (30-70 %) at low temperature (below 100 ˚C) or as diluted acids (between 0.1 % and 10 %) at high temperature (100 -250 ˚C). The first can accelerate a higher conversion rate of sugar (more than 90 %), however, are mostly very toxic and corrosive and thus require high operational and maintenance costs (Baruah et al., 2018). Among the acids, most studies found that diluted sulphuric acid (H_2SO_4) is mostly used to pre-treat the biomass.

Furthermore, alkali pre-treatment is based on the solubilization of lignin in the alkali solution (Baruah et al., 2018). This option is found to be more favourable for low lignin content of biomass such as herbaceous crops and agricultural residues but less productive for hardwoods. Alkali pre-treatment can effectively remove the lignin and generate carbohydrates more exposed to apply for downstream processes, although, the recovery of the chosen alkalis still requires further investigation.

Ozone pre-treatment is another way of reducing the lignin content of lignocellulosic wastes. The ozone can be applied for lignin (major) and hemicellulose (minor) degradation, excluding cellulose, in various types of lignocellulosic based of biomass (Kumar et al., 2009). This pre-treatment obtains an advantage where the reactions can be performed at room temperature and normal pressure. The ozone can be easily decomposed by applying the catalytic bed or by increasing the temperature to minimize the environmental pollution (Quesada, Rubio y Gómez, 1999). Nevertheless, ozone processes may result in a higher cost, compared to other chemical experiments, because it requires a large amount of ozone. Vidal & Molinier (1988) stated that the ozonation experiments have been mostly conducted in a hydrated fixed bed which result in more effective oxidations than aqueous suspension or suspensions in 45 % acetic acid.

Organosolv process is another promising way to pre-treat the biomass. In principle, it is based on the uses of organic solvents or aqueous solutions to break down the lignin and hemicellulose internal bonds, thus yielding a relatively pure cellulose residue (Baruah et al., 2018). According to Du et al. (2016), the delignification and solubilization process of hemicellulose will increase both the pore volume and surface area of cellulose as well as the accessibility of enzymatic hydrolysis and saccharification. The organic solvents which are usually used to pre-treat numerous types of biomasses include, i.e., ethanol, methanol, acetone, organic acid, organic peracid, and ethylene glycol or their mixture with water. This process is usually accompanied with additional catalyst, i.e., mineral acids, bases, or some salts, to reduce the temperature and to improve the delignification rate (Borand & Karaosmanoglu, 2018). Several advantages of using organosolv pre-treatment are as follows: i) the solvents are easily to be recovered from distillation; ii) the solvents can be recycled; and iii) the high-quality lignin isolated from this process can be utilized as value-added by-products for industrial applications (Baruah et al., 2018). However, this pre-treatment possesses several disadvantages. Firstly, the organic solvents are mostly expensive. To reduce the cost, Kumar et al. (2009) suggested to recycle the solvents which have been used in the process. Secondly, the need of quick recovery of these solvents requires an energy-intensive process. Thirdly, due to the high flammability and volatility of the organic solvents, the pre-treatment must be performed under controlled conditions (Borand & Karaosmanoglu, 2018).

In addition, producer can also apply the combination between the physical and the chemical method called physicochemical pre-treatment, i.e., the impregnation process where the biomass chips are mixed and soaked with a kind of alkali solution such as . This is aimed to increase the high carbon conversion rate at low temperature and pressure in the gasification process (Kumar et al., 2009; Yadav et al., 2020).

Finally, biological pre-treatment which exploits the lignin and hemicellulose degradation ability of various types of rot fungi such as brown-, white-, and soft-rot fungi. The first type of rots degrades mostly the lignin content; whilst, the middle and the latter type of rots mainly degrade both the cellulose and lignin contents (Kumar et al., 2009). The degradation capability of this fungi comes from their extracellular enzymatic systems involvement, that are hydrolytic and ligninolytic system. Hydrolytic system is associated with the degradation of cellulose and hemicelluloses; while ligninolytic system is responsible for the lignin depolymerization (Baruah et al., 2018). Since there is no inhibitor formation during the process, biological method relatively requires low cost and is eco-friendly (Sindhu, Binod &Pandey, 2016; Bhatia et al., 2017). However, in most biological processes, the rate of hydrolysis is very low (Kumar et al., 2009).

2.1.2. Biomass gasification

Biomass gasification can be characterised as a partial combustion because it involves with the stages of pyrolysis and partial oxidation in a well-controlled oxidizing condition to produce a synthesis gas (usually called syngas) (IRENA, 2021; Dahlquist, 2003). This syngas, in turn, shall be converted into liquid methanol (Vertes et al., 2010). Partial oxidation of biomass aims to generate the heat required for biomass drying, heating and pyrolysis. Rapagna et al. (2000) argues that by employing air and steam as the gasification agent, the syngas composition can be varied. can be utilized to increase and yields because it converts tar, char and methane substances into and/or (Ollero, 2003). To prevent the load of inert molecules in the syngas, pure oxygen (about 99 to 99.5 %) is usually used as the oxidising agent. The removal of inert molecules is performed to lower the plant costs by improving the efficiency and yield in the methanol synthesis as well as to reduce the size of the whole syngas handling system (IRENA, 2021). Because the amount of oxygen used – including its purity level – will directly affect the level of operation costs, methanol producer must take into account the trade-off between the input cost of high-purity oxygen, plant costs, methanol product yield, and electricity cost (IRENA, 2021).

In the process, biomass gasification is very flexible, i.e., i) its capability to process the inputs with different output qualities; and ii) the syngas produced is also extremely flexible depending on the processing design (Amaral et al., 2019). A techno-economic study of biomass to methanol production by Amaral et al. (2019) concluded that the production cost of methanol (plant capacity of 100 MW Lower Heat Value (LHV) biomass input) from biomass gasification is vary between € 350/ ton and € 440/ ton. Thus, the project is not feasible economically when the methanol market price is about € 350/ ton. However, the efficiency of biomass gasification to methanol production could be improved. Andersson, Lundgren & Marklund (2014) suggested that by integrating the pressurized entrained flow biomass gasification (PEBG) with the existing pulp and paper mill of black liquor gasifier, the overall plant efficiency increases approximately by 7 % compared to those of stand-alone PEBG. Thus, the production cost of methanol is lowered by the range of € 11 – 18/ MWh.

At the technological point of view, specific technology providers are the key to successfully generate high-quality syngas. According to Basu (2013), biomass gasification cost mainly depends on, to some extent, how to choose the gasifier technology types such as downdraft, updraft, side draft, bubbling fluidized bed, circulating fluidized bed, entrained flow, or supercritical water gasifier. Gasifier is a high-temperature converter unit of feedstock into syngas. The heat that is required for reactions is usually obtained by the combustion of some fractions of the biomass feedstock with pure oxygen. IRENA (2021) states that the gasifier unit usually consists of two or more parallel trains identically in design.

2.2. Synthesis gas purification and conditioning

The processes, that are relevant to the syngas purification and conditioning, typically include i) gas purification from particles and sulphur; ii) gas conditioning by balancing the H_2/CO ratio through water gas shift reaction; and iii) gas conditioning by removing the CO_2. The requirement for syngas purification is similar to that of Fischer-Tropsch synthesis (van der Drift & Boerrigter, 2006). However, this process may be done below the standard requirement due to the cost trade-off between gas cleaning and synthesis catalyst performance. Table 4 shows the maximum concentration of impurities allowed in syngas based from Fischer-Tropsch synthesis requirement (van der Drift & Boerrigter, 2006).

Table 4

Maximum concentration of impurities allowed in the syngas

Type of Impurity	Requirement
$H_2S + COS + CS_2$	< 1 ppmv
$NH_3 + HCN$	< 1 ppmv
HCL + HBr + HF	< 10 ppbv
Alkali metals (Na + K)	< 10 ppbv
Particles (soot and ash)	Almost completely removed
Organic components (viz. tar)	Not condensing: below dew point
Hetero-organic components (including S, N, and O)	< 1 ppmv

Source: van der Drift & Boerrigter, 2006

According to van der Drift & Boerrigter (2006), some of the methods to implement syngas purification include: i) particle (tar) removal by a filter or a cyclone; and ii) guard beds (ZnO and active carbon filters) to eliminate the trace impurities. In addition, a rectisol unit might be required if the CO_2 is needed to be removed. However, the Rectisol unit requires a pressurized gas and is only suited for large-scale plants. If a rectisol unit is not used, a kind of scrubbing process is then necessary to eliminate, i.e., the NH_3 (Clausen, 2011). Tar removal can be performed by either: i) tars catalytic or thermal cracking; ii) gas scrubbing process; or iii) steam reforming. The first is mostly preferred because it converts the tars to H_2 and CO as well as more energy efficient than thermal cracking (Clausen, 2011). It was applied by Larson, Jin & Celik (2009) and by the 20 MWth Skive BGGE/CHP plant in Denmark (Clausen, 2011). The scrubbing process was used in, i.e., the operating biomass gasification CHP Plants in Denmark and Austria (Zwart et al., 2009). While, steam reforming is effective when the tar content is very high – for example the gas generated from allothermal gasifier.

Syngas conditioning from water gas shift (WGS) reaction aims to improve the H_2/CO ratio of the syngas to meet the synthesis requirement (Giuliano, Freda & Catizzone, 2020; (Clausen, 2011). WGS is normally implemented after the steam reforming or partial oxidation. According to Clausen (2011), the optimal ratio for H_2/CO for methanol synthesis is 2 and 1 (mole basis) respectively. Nevertheless, these ratios might be adjusted depending on the gasifier specification used. For example, if the entrained flow gasifier is chosen for biomass gasification, the ratios will be about 0.6; but other gasifier types usually produce the syngas with higher ratio of H_2/CO which implies that the gas conditioning is not necessary.

The WGS is an exothermic reversible reaction that is normally performed, due to the thermodynamics constraint, in two separated reactors: high and low temperature shift reactor (Giuliano, Freda & Catizzone, 2020). The first reactor (between 310 ˚C and 450 °C, and 23-35 bar using iron/chromium catalytic system) aims to favour the kinetics, while the latter (between 200 °C and 240 °C using copper/zinc/alumina catalytic system) aims to favour the thermodynamics, such that the desired ratio of H_2/CO is met (Giuliano, Freda & Catizzone, 2020). When the CO_2 removal is needed for adjusting the syngas composition, the WGS can be integrated with the CO_2 absorption technology.

2.3. Methanol synthesis

After conditioning process is completed, the syngas is then converted into methanol through a catalytic process. The catalyst is generally based on copper, zinc oxide, and aluminium oxide types (Bertau et al., 2014; Olah, Goeppert & Prakash, 2018; Hansen, Nielsen & Haldor Topsoe, 2008). Finally, for methanol purification, the distillation of that crude methanol is implemented to remove the water and any by-products contents produced during the methanol synthesis (IRENA, 2021).

Methanol synthesis is performed in a reactor at elevated temperature and pressure. According to Clausen (2011), methanol can be produced either from the reaction of H_2 and CO as given in Eq. (6) or the reaction of H_2 and CO_2 as expressed in Eq. (7).

Pathways of methanol synthesis reaction:

$$1.\ 4H_2 + 2CO \leftrightarrow 2CH_3OH \qquad \Delta H = -181.6\ kJ \qquad (6)$$

$$2.\ 6H_2 + 2CO_2 \leftrightarrow 2CH_3OH + 2H_2O \qquad \Delta H = -99.6\ kJ \qquad (7)$$

High pressure is preferable to improve the reaction rate and to reduce the molar flow. In the other hand, the way of setting the temperature is greatly depending on the trade-off between the reaction rate and the molar flow of the chemical equilibrium (Clausen, 2011). In the isothermal reactor, the temperature for methanol synthesis is between 250˚C and 260˚C, depending on i) the reactor's type used; ii) syngas composition; and iii) the pressure setting (Haldor Topsoe, 2019). While, the pressure is set between 50 and 100 bar (Hansen, Nielsen & Haldor Topsoe, 2008).

Finally, to obtain a pure methanol product, the gaseous components generated from methanol synthesis, such as H_2, CO, CO_2, H_2O, inert types (i.e., N_2 and CH_4), and by-products from synthesis catalyst, need to be separated by condensation and distillation processes (Clausen, 2011).

3. The overview of biomass to methanol production cost

The financial planning of investment, including the production cost, for methanol plant is essential to gain the optimum profit. All expenses that are associated in every step of biomass to methanol processes are depending on numerous factor such as the feedstock type and condition, technology option, energy needs, production capacity, operating conditions, desired level of purity of the product, and availability of tax incentives (IRENA, 2021). These expenses, in general, are categorized into investment cost and operating cost. Investment cost, known as capital investment, is further divided into fixed-capital investment and working capital (Peters and Timmerhaus 2003).

Numerous studies which are related to assessing the production cost of methanol from biomass based have been performed. Mphoswa (2015), assessed the methanol production cost based on oxygen steam blown pressurized gasification with 450

MWLHV (548.7 MWHHV) biomass input of wood chips at 50% moisture. The biomass intake is about 189,360 kg/h or 1,514 kt/y, assuming 8,000 hours of operation per year. The biomass is converted into around 176,981 kg/h of gas which consists of H_2, CO, CO_2, H_2O, CH_4, N_2, O_2, Acetylene, Ethylene, Ethane, Propane, Benzene, Naphthalene, Ammonia, H_2S, and HCl. As a result, the methanol production is about 53,534 kg/h (336.8 MWHHV and 15,295.6 MWLHV) with efficiency of 61.3% HHV (65.7 % LHV) basis. The total capital investment of that biomass to methanol plant is presented in Table 5. While operating costs include i) fixed (i.e., operating labour, supervision, direct salary overhead, maintenance, property taxes and insurance, rent of land/buildings, general plant overhead, allocated environmental charges, running license fees and royalty payments, capital charges, and sales and marketing costs); and ii) variable (i.e., raw materials, utilities, consumables, effluent disposal, and shipping) costs. These total operating costs are given in table 5.

Table 5

Total capital investment of biomass to methanol plant

Type	Cost (million US$)
Gasification	43.25
Tar Reforming and Quench	26.94
Acid Gas and Sulphur Removal	28.49
Syngas Compression and Expansion	60.63
Methanol Synthesis	41.42
Separation	20.32
Steam System and Power	45.84
Cooling Water and Other Utilities	9.56
Total	276.45
Total including Operating Costs, Land and Basic Infrastructure	367.23

Source: Mphoswa, 2015

Table 6

Total operating costs of biomass to methanol plant

Type	Cost (million US$)
Management and Liability Insurance	1.69
Marketing and Other	1.00
Operational (Raw Material and Utilities)	47.56
Employee Benefits and Utilities	20.55
Total	70.80

Source: Mphoswa, 2015

Furthermore, in terms of the unit cost of methanol production, according to US DOE (2016), is briefly presented in table 7. The unit costs are derived based on the assumption that the process design is via indirect liquefaction (IDL) pathway that involves less-severity operating conditions in the methanol synthesis of the plant. Thus, the project is considerably more economically competitive.

Table 7

Unit cost projection of methanol plant via indirect liquefaction design case

Type	Unit Cost ($/GGE) Projection 2022
Feedstock	$ 1.37
Gasification	$ 0.50
Synthesis Gas Clean up (Reforming and Quench)	$ 0.84
Acid Gas Removal, Methanol Synthesis Conditioning	$ 0.39
Hydrocarbon Synthesis	$ 0.38
Hydrocarbon Product Separation	$ 0.04
Balance of Plant	-$ 0.06
MFSP	$ 3.47

*Note: GGE = Gallon Gasoline Equivalent, SoT = annual State of Technology assessment, MFSP = Minimum Fuel Selling Price, in US$ 2014. Source: US DOE (2016).

IRENA (2021) presented the variation of capital expenditure of methanol production as an end product based on the global existing projects, that is given in table 8. The capital expenditure per unit per year of bio-methanol produced is shown in table 9.

Table 8

The capital cost for bio-methanol plants

Nº	Project/study	Status	Capacity (kt/y)	Investment (million US$)	Investment (US$/t/y)	Investment (US$/kW)	Source
1.	Trans World Energy (TWE), US	Feed done, start-up Q2 2023	875	430	490	710	TWE
2.	ENI Refinery, Italy	Basic Engineering ready Q3 2020	115	330	2,900	4,280	NextChem
3.	LowLand Methanol, Netherland	Start-up early 2023	120	130	1,110	1,620	LowLand Methanol
4.	Sodra, Sweden	Operational	5	11	2,220	3,230	Sodra
5.	Enerkem, Netherland	Engineering	215	580	2,690	3,840	Enerkem
6.	Enerkem, Spain	Engineering	215	580	2,690	3,840	Enerkem
7.	VTT	Detailed study	265	385	1,450	2,070	VTT
8.	Chemrec, Domsjo (Sweden)	Preliminary Engineering	147	390	2,640	3,400	Chemrec
9.	Chemrec, nth plant	Concept	290	540/270*	1,880/930*	2,740/1,370*	Chemrec
10.	New Hope Energy, US	Investment decision Q4 2020	715	500	700	1,020	New Hope Energy

* This investment is credited for the avoided investment in a new recovery boiler. Source: IRENA (2021)

Table 9

Bio-methanol unit production cost

Capex/unit/y	From Biomass	
	Low	High
US$/t Methanol	206	293
US$/MWh Methanol	37	53
US$/GJ Methanol	10.4	14.7

Source: IRENA (2021).

According to Brown et al. (2020), a typical price of woody biomass in Europe and the US is between EUR 50 and 100 per dry ton or between US$ 3 and 6; while in southern US, parts of Canada and Brazil, the price is lower between EUR 25 and 50 per dry ton or between US$ 1.5 – 3/GJ. The unit cost of methanol production based on the feedstock cost and conversion varieties is shown in table 10.

Table 10

Unit cost of biomass-methanol based on conversion efficiency and feedstock cost varieties

Feedstock cost US$/GJ feedstock	Unit Cost of Methanol Based on the Conversion Efficiency					
	50%		60%		70%	
	US$/GJ	US$/t	US$/GJ	US$/t	US$/GJ	US$/t
15	30.0	597	25.0	498	21.4	426
10	20.0	398	16.7	332	14.3	286
6	12.0	239	10.0	199	8.6	171
3	6.0	119	5.0	100	4.3	85
1.5	3.0	60	2.5	50	2.1	43

Source: IRENA, 2021

In terms of Operational Expenditure (OPEX), IRENA (2021) argued that OPEX other than feedstock is usually not specified in literatures. Herein, this information is often aggregated and given as an annual percentage of total investment cost or CAPEX. IRENA (2021) suggested the OPEX low and high ranges between 5 % and 10 % as shown in table 11.

Table 11

The OPEX of bio-methanol production

		Biomass Feedstock	
		Low	High
	Unit CAPEX, US$/t Methanol/y	1,560	2,220
OPEX Low	5%	78	111
OPEX High	10%	156	222

Source: IRENA, 2021

In addition, the production cost of bio-methanol from wood pulping is presented in Table 13. Compared to the usual plant, the relevant OPEX will rise another US$ 60 – 120/t. Therefore, the production cost of methanol as by-product from wood pulping increases between US$ 540 and 800/ton.

4. Methanol supply-chain issues and recommendation: a review

Biomass to methanol production as an alternative approach in replacing fossil fuels in the transportation sector is available, but limited and at a high cost (Clausen, 2011). According to IRENA (2014), to generate 135 MT of bio-methanol through gasification requires 230 MT of dry biomass. The production cost of methanol from biomass feedstock currently remains higher than that of fossil-based (natural gas or coal) (IRENA, 2021). One of the issues is that the policy schemes often apply only in short-term and/or quota-based which will be difficult to support the long-term price. The environmental issues include, among others, the land availability, competition with food and other crops, as well as environmentally sustainability – i.e., the effects on soil quality, soil erosion, need for water and fertilisers, biodiversity concerns, land tenure and emissions of pollutants to air and water (IRENA, 2021). In addition, the seasonality harvest of the biomass feedstock needs to be addressed either by storage application or feedstock diversification to avoid plant idling or shut down.

A well-designed supporting policies and incentives are important to attract the capital-intensive renewable technology investment in long terms (IRENA, 2021). In Indonesia, methanol has been considered as clean energy alternative to support its national energy security (Ministry of Mineral and Energy Resources MEMR, 2021). In year 2019, Indonesian methanol demand reached 1.1 million tons. On the supply side, however, its annual production was only about 660,000 tons (Ministry of Industrial, 2020). To increase this methanol supply, currently, the Indonesian planning development of methanol plant uses only coal as feedstock. While, biomass-based methanol production has not yet included in this national pioneered agenda. It is projected that coal to methanol plant of about 1.8 million tons will be developed in East Kutai using 4.7 – 6.1 million tons of coal feedstock. The methanol product is also expected to be reprocessed for Dimethyl Ether (DME) production (Ministry of Industrial, 2020).

Methanol can also be used as the feedstock for various petrochemical products, i.e., acetic acid, formaldehydes, Methyl Tertiary Butyl Ether (MTBE), polyvinyl, polyesters, rubber, resin synthetic, pharmacy products, DME, and others. Therefore, the development of methanol industry is essential to improve i) Indonesian independency on petrochemical; ii) national competitiveness; iii) national industrial sustainability; and especially iv) to reduce significantly deficit trade account due to current net-import position in Indonesia (Indonesian Chamber of Commerce, 2020). In the last 2 decades, the investment status for Indonesian petrochemical sector is considerably low, which in turn, petrochemical feedstock still relies on import supply. To fulfil the national demand of methanol, Indonesia's methanol import reaches approximately 12 billion US$ or equivalent to IDR 174 trillion per year. Currently, the domestic production of petrochemical is only about 2.45 million tons; whilst the relevant domestic demand reaches about 5.6 million tons annually. In other words, the shares of domestically produced of petrochemical feedstock is only about 47 % of its national demand.

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