ETSAP
ENERGY TECHNOLOGY SYSTEMS ANALYSIS PROGRAMME

IRENA
International Renewable Energy Agency

Production of Bio-methanol

Technology Brief

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About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organization dedicated to renewable energy. In accordance with its Statute, IRENA's objective is to "promote the widespread and increased adoption, and the sustainable use of all forms of renewable energy". This concerns all forms of energy produced from renewable sources in a sustainable manner and includes bioenergy, geothermal energy, hydropower, ocean, solar and wind energy.

As of December 2012, the membership of IRENA comprises some 160 States and the European Union (EU), out of which 104 States and the EU have ratified the Statute.

About IEA-ETSAP

The Energy Technology Systems Analysis Programme (ETSAP) is an Implementing Agreement of the International Energy Agency (IEA), first established in 1976. It functions as a consortium of member country teams and invited teams that actively cooperate to establish, maintain, and expand a consistent multi-country energy/economy/environment/engineering (4E) analytical capability.

Its backbone consists of individual national teams in nearly 70 countries, and a common, comparable and combinable methodology, mainly based on the MARKAL / TIMES family of models, permitting the compilation of long term energy scenarios and in-depth national, multi-country, and global energy and environmental analyses.

ETSAP promotes and supports the application of technical economic tools at the global, regional, national and local levels. It aims at preparing sustainable strategies for economic development, energy security, climate change mitigation and environment.

ETSAP holds open workshops twice a year, to discuss methodologies, disseminate results, and provide opportunities for new users to get acquainted with advanced energy-technologies, systems and modeling developments.

Insights for Policy Makers

Methanol is one of the most important and versatile platform chemicals for chemical industry. It is mainly used to produce other chemicals, such as additives for gasoline, solvents and anti-freezes, or in the biodiesel production process. Current research efforts focus particularly on how to use methanol to produce transportation fuels (e.g. after conversion to dimethyl ether) and plastics.

The current global methanol production is about 45 million tonnes per year and is mostly based on fossil fuels, mainly natural gas. However, methanol can also be produced from other carbon-containing feedstock, including biogas, biomass, waste streams and CO_2. Bio-methanol (also called renewable methanol) is chemically identical to conventional methanol. The main advantage of bio-methanol is the reduction of fossil fuel use and greenhouse gas emissions compared to conventional methanol production and the possibility to convert (by gasification) a range of renewable feedstock into bio-methanol. However, the production cost of bio-methanol is estimated between 1.5-4.0 times higher than the cost of natural gas-based methanol, which, at current fossil fuel prices, ranges from €100-200/t. Bio-methanol production costs also depend heavily on feedstock prices, plant set-up and local conditions.

Current bio-methanol demonstration projects focus mainly on using waste and by-product streams from other industrial processes, such as feedstock, which offer the best economics. Particularly glycerin, a by-product from biodiesel production, and black liquor from the pulp and paper industry are considered as the basic feedstock. A commercial-scale plant producing bio-methanol from glycerin is in operation in the Netherlands. In Iceland, renewable methanol is also produced by combing hydrogen and CO_2. Other potential feedstock includes biogas from landfills or solid organic waste, and bagasse (i.e. milled sugarcane fiber). The current demonstration projects benefit from favourable conditions, such as low feedstock prices (e.g. glycerin), strong integration with conventional industrial processes (e.g. pulp and paper) or very inexpensive renewable electricity (e.g. Iceland). Depending on the presence of appropriate local conditions, other early or niche opportunities for bio-methanol production exist (e.g. integrated production with bio-ethanol from sugarcane, co-feeding biomass feedstock and fossil fuels, and co-production of heat, electricity and other chemicals).

The use of locally grown biomass for methanol production can make countries less dependent on fossil energy imports, reduce greenhouse gas emissions compared to methanol production from fossil fuels, and stimulate local economies and employment. Co-feeding of renewable feedstock in natural gas- or coal-based

methanol production facilities can be used to gradually introduce bio-methanol production and reduce the environmental impact of conventional methanol production.

However, the use of biomass feedstock to produce bio-methanol may compete with the use of biomass for other products and commodities, such as biofuels for transportation, electricity and heat from biomass, and other biomass-based products, such as biogas, chemicals and plastics. In this situation, it is important that the available biomass feedstock is used in an optimal way. One way to promote the optimal use of biomass is to fully credit the environmental advantages across the entire life cycle, from feedstock production to the end-use. A range of policy options, including eco-labeling, incentives, carbon tax and information campaigns, can help promote the optimal use of the biomass resources.

Highlights

- **Process and Technology Status –** Methanol is one of the most important platform chemicals produced by the chemical industry. Presently, methanol is used to make various other chemicals, converted into anti-knocking agents and blended with fuels, and applied as a solvent and anti-freeze. Current research is looking into possibilities to use methanol as a transportation fuel (e.g. after conversion to dimethyl ether), as an energy carrier in general in a so-called *methanol economy*, and for the production of other basic chemicals (i.e. ethylene, propylene). The present global production of 45 million tonnes per year is based almost entirely on fossil fuels, mainly natural gas. Concerns over climate change, fossil fuel depletion and natural gas prices have sparked interest in using renewable feedstock for the production of bio-methanol. Bio-methanol can be produced from virgin or waste biomass, non-biogenic waste streams or even CO_2 from flue gases. These feedstocks are converted (typically through gasification) into syngas, a mixture of carbon monoxide, hydrogen and other molecules. The syngas is subsequently conditioned through several steps to reach the optimal composition for methanol synthesis (e.g. by removing CO_2 or adding hydrogen). To decrease the environmental impact of bio-methanol production, it has been proposed to use renewable electricity to supply the required hydrogen through electrolysis. Bio-methanol is chemically identical to conventional methanol. At present, about 200,000 tonnes of bio-methanol are produced per year. However, plans exist to increase the global capacity to well over one million tonnes within a few years.

- **Performance and Costs –** Assessing the environmental performance of bio-methanol is difficult since the technology is still evolving and performance is highly dependent on the plant set-up, the feedstock used and the consideration of potential co-products. However, many scientific studies have modeled bio-methanol production using a wide range of assumptions. These studies estimate that bio-methanol could reduce greenhouse gas emissions by 25-40% compared to methanol from fossil fuels if the entire life cycle is taken into account. Furthermore, co-producing heat, electricity or other chemicals has been suggested to improve bio-methanol's economic performance. In addition, when bio-methanol is produced from industrial organic waste streams, feedstock logistics are simplified and total plant economics can be improved. Finally, it is possible to co-feed biomass into a coal-based gasifier, or biogas into a natural gas-based methanol plant. These co-feeding options can be used to make methanol production gradually more sustainable. The production costs of bio-methanol are also highly dependent on the feedstock used, plant set-up and local conditions. Compared to the natural gas-based methanol production (with costs as low as €100-200 per tonne), bio-meth-

anol production costs are estimated to be 1.5-4 times higher in the scientific literature. Wood-based bio-methanol costs are estimated from as low as €160/t to as high as €940/t. When using waste streams, the production costs are estimated to be slightly lower; between €200-500/t. Production based on CO_2 is estimated to be very expensive, between €510-900/t. Current bio-methanol projects focus mainly on using waste streams from other industrial processes, suggesting that those can offer the best economics. The presence of other niche opportunities depends on specific local conditions (e.g. very low electricity prices).

- **Potential and Barriers –** At present, the high production cost and capital investment required for bio-methanol limit its commercial application. However, further research into gasification technologies is expected to improve its economics. Because the cost of bio-methanol will always be compared to that of natural gas-based methanol, higher natural gas prices and reduced fossil fuel subsidies will benefit the implementation of bio-methanol in the chemical sector. Furthermore, current policies for CO_2 accounting consider only the onsite emissions for the chemical sector. The main environmental advantage of methanol from biomass (i.e. uptake of atmospheric CO_2 in the plant growth phase) is therefore not included here. Therefore, policies should credit the CO_2 benefits of a product over its entire life cycle to accurately reflect the environmental advantages of bio-based chemicals.

Process and Technology Status

Methanol (CH_3OH) is an important basic chemical. It is produced from fossil fuels, such as natural gas, coal and oil products (e.g. heavy refinery residues, naphtha) and used in the production of a wide range of products. In 2010, about 70% of methanol was used in the chemical and petrochemical industry to produce chemicals (MI, 2010b), such as formaldehyde and acetic acid, ending up in polymers, such as polyethylene terephthalate (PET) and polyurethane (PUR). In addition, methanol is converted into methyl-tert-butyl-ether (MTBE) and tert-amyl-methyl-ether (TAME) as an anti-knocking additive, and used as a solvent and anti-freeze. More recently, methanol has also been used for biodiesel production from fats and oils, and it is increasingly being investigated as a clean-burning transportation fuel, either directly blended with conventional fuels or after conversion into dimethyl ether (DME). The application of methanol in the transport sector has risen from 4% of global production in 2005 to 23% in 2010 (MI, 2010a). The possibility of converting methanol into other basic chemicals (e.g. ethylene, propylene) is also being investigated. This methanol-to-olefins (MTO) process is mainly being implemented in China.

The global methanol production currently amounts to about 45 million metric tonnes (Mt) per year (MI, 2010b). Major producers with large-capacity plants (up to 5,000-6,750 metric tonnes per day) are China, the Middle East, Russia and Trinidad and Tobago (Meyers, 2004). About 80% of methanol production is based on natural gas while the rest is based on coal (17%) and small amounts of oil (MI, 2010b). Particularly in China, where large coal reserves are available, coal-based methanol capacity (i.e. currently about 9 Mt/yr) is rapidly increasing, with applications as a fuel for transport and in the MTO process (Wang, 2009).

The increasing oil and natural gas prices in recent years, as well as concerns about greenhouse gas (GHG) emissions, have sparked growing interest in alternative processes for methanol production based on renewable sources. Alternative feedstock includes biomass, waste and by-products from various sectors, such as biogas from landfill, sewage, solid waste treatment, glycerin (glycerol) from biodiesel production, and black liquor from the pulp and paper industry. Bio-methanol[1] from renewable sources and processes is chemically identical to fossil fuel-based methanol but involves significantly

1 In this brief, the term "bio-methanol" refers to both methanol produced from renewable resources and "renewable methanol" produced from CO_2.

lower GHG emissions during the entire lifecycle[2]. In addition, the use of bio-methanol can reduce the dependency on fossil energy imports and stimulate local economies. This technology brief mainly focuses on bio-methanol as a replacement for fossil fuel-based methanol in the chemical industry.

- **Production Process –** Methanol can be produced from concentrated carbon sources, such as natural gas, coal, biomass, by-product streams or even carbon dioxide (CO_2) from flue gases (Galindo Cifre & Badr, 2007). A simplified overview of the steps involved in methanol production is given in Figure 1. In general, the plant configurations used for bio-methanol production show strong similarities to coal-based methanol production via gasification, with two notable exceptions: bio-methanol from bio-gas (which is similar to methanol production from natural gas) and bio-methanol from CO_2. The main processes in a conventional methanol plant are: gasification, gas cleaning, reforming of high hydrocarbons, water-gas shift, hydrogen addition and/or CO_2 removal, and methanol synthesis and purification (Hamelinck & Faaij, 2002). If the feedstock consists of primary biomass, a pre-treatment of the raw material may be required (e.g. chipping and drying of woody biomass or purification of liquid feedstock).

  The feedstock is then gasified into synthesis gas (syngas), a mixture of mainly carbon monoxide (CO) and hydrogen (H_2), as well as carbon dioxide, water (H_2O) and other hydrocarbons. Using a limited amount of oxygen during feedstock heating (i.e. above 700°C) will improve the formation of CO and H_2 and reduce the amount of unwanted CO_2 and H_2O. However, if air is used as a source of oxygen, inert gases (e.g. nitrogen) increase the gas flow through the gasifier and downstream equipment (Mignard & Pritchard, 2008), thus resulting in higher equipment (investment) costs (Hamelinck & Faaij, 2006). On the other hand, using pure oxygen is rather expensive[3]. Therefore, an economic optimum is to be found between oxygen purity and production costs based on electricity prices and equipment costs.

  After gasification, impurities and contaminants (e.g. tars, dust and inorganic substances) are removed before the gas is passed through several condition-

2 The life cycle of a product includes all steps involved in its manufacture, use and disposal after use (waste management). Life cycle analysis enables a full understanding of the environmental impact of the product.

3 Oxygen is typically produced via cryogenic air separation (large capacities that are well-suited for methanol production), pressure swing adsorption (PSA, small- to mid-size capacity), or electrolysis.

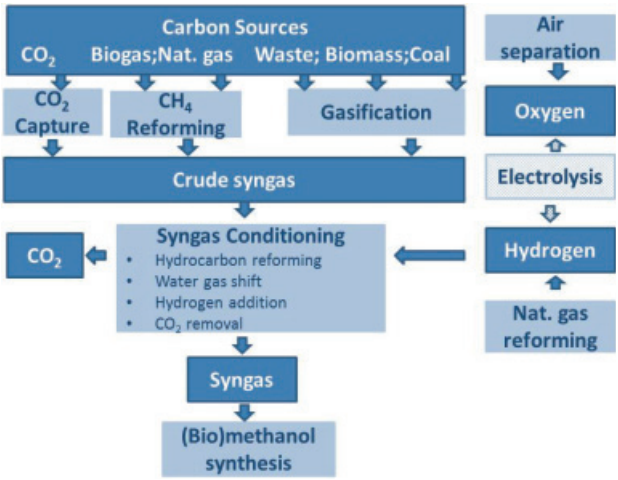

Figure 1 – Overview of Major Methanol Production Processes from Various Carbon Sources

ing steps that optimise its composition for methanol synthesis (see Figure 1). The aim of the syngas conditioning step is to produce syngas that has at least twice as many H_2 molecules as CO molecules (Specht & Bandi, 1999). The optimal ratio of H_2 molecules to CO molecules depends on the initial syngas composition, as well as the availability of H_2.

The initial syngas composition depends on the carbon source and gasification method (Galindo Cifre & Badr, 2007). The concentrations of CO and H_2 can be altered in several ways. First, unprocessed syngas can contain small amounts of methane and other light hydrocarbons with high energy content. These are reformed to CO and H_2 (Hamelinck & Faaij, 2006) by high temperature catalytic steam reforming or by auto-thermal reforming (ATR). These reform processes can lead to the formation of carbonaceous residues that reduce the performance of catalysts, and there is currently no consensus on which option is more cost-effective (Hamelinck & Faaij, 2006).

Second, the initial hydrogen concentration in the syngas is usually too low for optimal methanol synthesis. To reduce the share of CO and increase the share of H_2, a water gas-shift reaction (WGSR) can be used to convert CO and H_2O

into CO_2 and H_2. CO_2 can also be removed directly using chemical absorption by amines. Other CO_2 removal technologies (e.g. adsorption onto liquids, cryogenic separation and permeation through membranes) are being developed, but more time is needed for practical applications (Olah et al., 2009).

Third, hydrogen can be produced separately and added to the syngas. Industrial hydrogen is produced either by steam reforming of methane or electrolysis of water. While electrolysis is usually expensive, it can offer important synergies if the oxygen produced during electrolysis is used for partial oxidation in the gasification step, thus eliminating?? the need for air or oxygen production from air separation (see Figure 1). However, from an environmental point of view, it is estimated that electrolysis only makes sense if renewable electricity is available (Specht et al., 1999; Clausen et al., 2010)[4]. In addition, if electrolysis provides precisely enough oxygen for the gasification, the associated hydrogen production is not enough to meet the optimal stoichiometry in the syngas. Therefore, CO_2 removal might be needed anyway to obtain an optimised syngas (Specht & Bandi, 1999).

After conditioning, the syngas is converted into methanol by a catalytic process based on copper oxide, zinc oxide or chromium oxide catalysts (Hamelinck & Faaij, 2006). Distillation is used to remove the water generated during methanol synthesis. An overview of major methanol production processes from various carbon sources is presented in Figure 1, with the most important inputs and outputs, and the possible addition of electrolysis[5].

The technologies used in the production of methanol from biomass are relatively well-known since they are similar to the coal gasification technology, which has been applied for a long time. However, making biomass gasification cost-competitive has proven difficult (see also the Cost section). Table 1 provides an overview of facilities (in operation or planned) that produce bio-methanol. Technically, any carbon source can be converted into syngas, but current projects for bio-methanol mainly focus on using by-products from

4 Electrolysis is an electricity-intensive process to co-produce hydrogen and oxygen, requiring about 48-60 kWh/kg H_2 (IEA, 2007). Therefore, obtaining hydrogen through electrolysis will create significant CO_2 emissions when non-renewable electricity is used.

5 Note that not all the syngas conditioning steps shown in Figure 1 are always required for methanol production and depend on the composition of the crude syngas. For example, the water gas-shift reaction might not be needed if the ratio of H_2 versus CO is higher than two in the crude syngas.

Table 1 – Overview of Existing or Planned Facilities for Bio-methanol Production [a]

Location	Company	Start-up year	Capacity kt/yr	Main Product	Feedstock type	Source
Operational						
Netherlands	BioMCN	2010	200[a]	Bio-methanol	Glycerin	BioMCN, 2010
Sweden	BioDME[c]	2011	1.5[c]	Bio-DME	Black liquor	BioDME, 2011
Canada	Enerkem	2011	4	Syngas, bio-methanol	Treated wood	Enerkem, 2011
Under construction/Proposed						
Iceland	Carbon Recycling International	2011	1.6	Bio-methanol	Flue gas CO_2	CRI, 2011
Canada	Al-Pac[d]	2012	4	Paper pulp	Wood	Rabik, 2011; Al-Pac, 2011
Canada	Enerkem	2012	29[e]	Bio-ethanol, bio-methanol	Municipal solid waste	Enerkem, 2011
Sweden	Chemrec & Dom-sjöFabriker	Late 2012	100[f]	Bio-DME, bio-methanol	Black liquor	Chemrec, 2008
Sweden	Värmlands Metanol	2014/2015	100	Bio-methanol	Forest residue	Värmlands Metanol, 2011
Netherlands	Woodspirit[g]	2015	400-900[g]	Bio-methanol	Wood	CHE, 2011; Bio-refining, 2011
Poland	PKE & ZAK[h]	2015	Up to 550	Heat & Power, Chemicals	Up to 10% biomass, coal	ZAK & PKE, 2009
Germany	DeBioM			Bio-methanol	Wood	DeBioM, 2011

a) Table 1 is based on publicly available information, which could be obsolete or incomplete. Only plants producing bio-methanol are included. However, in principle, any syngas-producing facility based on biomass or waste streams can be converted to produce bio-methanol. A complete overview of biomass gasification projects can be found in IEA (2011) or NETL (2010).
b) Upscaling to 400 kt/yr bio-methanol capacity expected by 2013 (CHE, 2011).
c) BioDME is a temporary consortium that aims to prove the feasibility of bio-DME production from black liquor for transportation purposes. Capacity figure refers to bio-DME and is estimated based on a pilot plant with a daily production capacity of four tonnes.
d) Alberta Pacific Forest Industries, Inc. is already producing unpurified bio-methanol in its pulping process. Although it is currently burned as a fuel, a new installation will purify the bio-methanol so that it can be used internally and sold.
e) Combined bio-methanol and bio-ethanol capacity.
f) Combined bio-DME and bio-methanol capacity.
g) Consortium of BioMCN, NOM, Linde, Visser & Smit Hanab and Siemens; proposed bio-methanol capacity unclear.
h) Consortium of utility company Południowy Koncern Energetyczny and chemical producer Zakłady Azotowe Kędzierzyn. The proposed IGCC plant will co-produce electricity and heat, while produced CO2 will be stored underground (66%) and chemically sequestered in chemicals, such as (partially bio-based) methanol and urea (26%).

other industrial processes (see column 6) as this offers several advantages (Ekbom et al., 2005). For example, the integration of bio-methanol production into another facility simplifies the feedstock supply and logistics and shares the associated costs. In addition, the overall economics of an integrated plant are less sensitive to price fluctuations of one of its products. Apart from black liquor from pulp processing (Naqvi et al., 2012) and glycerin from biodiesel production, bagasse (i.e. milled sugarcane fiber from bio-ethanol production) and municipal solid waste can also be used as bio-methanol feedstock (Clausen, 2010; Bromberg & Cheng, 2010).

Performance and Sustainability

Performance of bio-methanol plants depends on many factors, such as the plant set-up (e.g. feedstock, co-products, technology) and local conditions (e.g. availability of feedstock or renewable electricity). Assessing real life performance is difficult as only a limited number of commercial plants are currently in operation (Table 1). Different models based on various assumptions can be utilised to investigate different plant configurations in specific locations (e.g. Hansen et al., 2011). This leads to a range of estimates for efficiency and environmental impact that are often difficult to compare.

An option which could be economical would be to mix renewable and fossil feedstocks (co-feeding). This can gradually make methanol production environmentally friendly and increase the expertise in biomass-based methanol production. Several ways in which feedstocks can be mixed have been proposed.

First, a specific syngas composition can be reached by combining syngas from different sources or gasifying different feedstocks simultaneously. The crude syngas from biomass usually has a low hydrogen : to-carbon (H/C) ratio, whereas syngas from natural gas has a very high H/C ratio. The combination of the two syngas streams can therefore be optimised in such a way that the water-gas shift reaction and/or the CO_2 removal step are no longer needed, thus leading to capital cost savings (Li et al., 2010). For example, this can be done in integrated gasification combined cycles (IGCC), which are traditionally used for coal gasification. The IGCC plants can gasify a mix of coal and biomass or waste streams. An example of such a methanol production facility was the Schwarze Pümpe plant in Germany, which is no longer in operation (Sander et al., 2003).

Second, biogas can replace natural gas in current methanol production plants (Kralj & Kralj, 2009), although the biogas-to-methanol route has not yet been commercialised. While the production process is largely similar, some technical changes are needed because biogas typically contains a larger share of CO_2 (e.g. 25-45%) (AEBIOM, 2009) than natural gas, which impacts the composition of the crude syngas. In addition, hydrogen sulfide must be removed. Waste anaerobic digestion to produce biogas for methanol production could also be a viable and cost-effective method, particularly in developing countries where waste management systems are still developing.

Another option to increase economic and environmental performance of bio-methanol production is the co-production of other forms of energy or chemicals. For example, co-generation of electricity (Li et al., 2010) and heat for district heating (e.g. Clausen et al., 2010) are often included in plant designs as they can increase energy efficiency and revenues. Chemicals co-production can also improve economics and energy efficiency. Bio-methanol can be co-produced along with hydrogen (Kralj, 2011; Ohlström et al. 2001), bio-ethanol (Kraij, 2008; Reno et al., 2011; Enerkem, 2011) and urea (ZAK & PKE, 2009). The integration with CO_2 capture has also been studied (Meerman et al., 2011).

- **Efficiency and Emissions –** The production of bio-methanol will reduce the need for fossil fuel and nuclear energy consumption and will reduce greenhouse gas (GHG) emissions. The achievable savings in fossil and nuclear energy and GHG emissions (on a cradle-to-factory-gate basis) are considered key indicators for the environmental impact of bio-based products. Related figures for bio-methanol production are scattered as most literature sources focus on technical issues and production cost estimates. The energy efficiency of methanol production from natural gas ranges from about 60-70% (Biedermann et al., 2006; Hansen, 2005). For methanol production from natural gas, petroleum products and coal, the process energy ranges between 29-37 gigajoule (GJ) per tonne, including feedstock use (UNIDO, 2010), depending on the feedstock mix and regional variations in energy efficiency.

  For methanol from biomass and coal, the energy efficiency is estimated to be lower, between 50-60% (Bromberg & Cheng, 2010). This is due to the lower H/C ratio of the feedstock, as well as higher ash and char contents. In general, the overall energy efficiency of a bio-methanol plant will depend on which process steps are included, whether electricity and/or heat are co-produced, and on the size of the plant (Galindo Cifre & Badr, 2007).

A range of estimates of the non-renewable energy[6] consumption for bio-methanol production exists in the literature as a result of different assumptions about the production process. For example, some studies assume that the required process energy (i.e. steam and electricity required to run the process) is co-produced from biomass (e.g. Ekbom et al., 2005), meaning that no non-renewable energy is used for bio-methanol production. Conversely, others assume that non-renewable energy sources are used (in particular for electricity requirements). In reality, the non-renewable energy required per tonne of methanol will also depend on the plant set-up.

Estimates of CO_2 emissions from bio-methanol production in the literature also vary widely based on different assumptions. Majer and Gröngröft (2010) estimated that in Germany the production based on short rotation coppice (0.64 kg CO_2eq/kg bio-methanol) and forest residues (0.56 kg CO_2eq/kg bio-methanol) can lower cradle-to-factory-gate GHG emissions by 24% and 33%, respectively, compared to methanol from natural gas (0.84 kg CO_2eq/kg methanol). In addition, Dowaki and Genchi (2009) estimate that Japanese wood-based bio-methanol production can achieve CO_2 emission reductions of 24-40% compared to natural gas.

Current Costs and Cost Projections

- **Production Cost –** The production costs of bio-methanol are also highly sensitive to local conditions. Key factors that influence the currently available estimates are feedstock types and prices, electricity generation fuel mix and prices, scale of production capacity, technology choice and investment costs, and the desired grade of the final product.

  Local conditions often influence which technologies are to be used in a new plant (as discussed in the process description) and have a significant impact on the production costs, meaning that the ideal plant set-up differs according to the location. For example, the electricity cost can make up between 23-65% of the production cost of bio-methanol, depending on the plant set-up (Clausen et al., 2010). The high end of this range refers to plants utilising CO_2 as feedstock along with electrolysis. This is the case, for example, for a

6 Non-renewable energy refers to both fossil and nuclear energy sources.

production plant in Iceland (see Table 1). Electrolysis requires a lot of electricity, but if the price of electricity is very low, a bio-methanol facility using electrolysis can become an economically attractive option. For example, in Iceland, 80% of electricity comes from low-cost geothermal and hydropower sources, with little GHG emissions. This exceptional situation demonstrates the importance of local conditions and shows that early opportunities for cost-effective bio-methanol may already exist.

The factors mentioned above translate into a wide range of production cost estimates. Figure 2 provides an overview of such estimates for methanol production from various feedstocks as found in the literature. The estimates in Figure 2 reflect the original assumptions regarding energy prices, technology, performance and co-product credits.

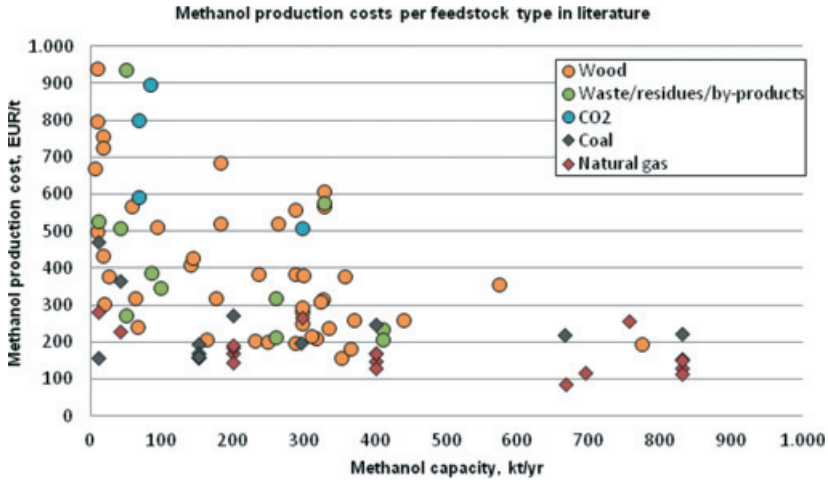

Figure 2 – Production Costs and Production Capacity of (Bio-)methanol for Various Feedstocks from the Literature

Source: IRENA analysis. Excludes co-feed set-ups; all costs converted to 2010 Euro values using national GDP deflators (World Bank); assumed OECD average inflation if no specific region is mentioned; assumed 8,000 operational hours per year (if necessary); for costs beyond 2010, 2.5% annual inflation was assumed (OECD average for 1995-2010). Based on Air Products (1998; 2004), Amigun et al. (2010), Barrañon (2006), Clausen et al. (2010), Ekbom et al. (2003; 2005), Hamelinck & Faaij (2006), Heydorn et al. (2003), Hokanson & Rowell (1977), Huisman et al. (2011), Intille (2003), Kim et al. (2011), Kraaij (2008), Leduc et al. (2009; 2010), Mignard & Pritchard (2008), Roan et al. (2004), Sarkar et al. (2011), Specht et al (1998; 1999), Tock et al. (2010), Ohlström et al. (2001), Williams et al. (1995) and Xiao et al. (2009).

The costs of methanol production from fossil fuels (i.e. red and black points in Figure 2 for natural gas and coal, respectively) range from €75-250/t for natural gas, and from €150-300/t for coal[7]. A global weighted average (i.e. IRENA's bottom-up estimate) is estimated at about €160/t, with a production capacity of about 830 kt per year. However, coal-based, small-scale production (up to 200 kt/yr) can involve significantly higher costs of up to € 470/t.

The costs of bio-methanol production based on wood, waste streams and CO_2[8] are shown in Figure 2 by orange, green and blue points. The cost of wood-based bio-methanol production is estimated to range from €160/t (Hamelinck & Faaij, 2006) to € 940/t (Tock, 2010). This large range stems from different assumptions about plant set-ups and local conditions. Figure 2 also suggests that economies of scale play an important role for wood-based bio-methanol production, as cost estimates at a higher annual production capacity are significantly lower. For example, few estimates above €400/t exist for capacity levels higher than 300 kt/yr, although fewer data points are available for this large-scale production. Disregarding outlier data points in Figure 2 (i.e. €940/t and €580/t), the production costs for bio-methanol from waste streams are slightly lower compared to wood: between €200-500 per tonne. While data points are scarce, the production costs again appear lower for higher capacities, with a smaller spread. The production of bio-methanol from CO_2 is estimated to be the most expensive production process, with figures ranging between €510-900/t.

Figure 2 shows that bio-methanol from wood or waste streams can only compete with coal-based production in the most optimistic cases and is always more expensive than natural gas. Compared to the cheapest fossil fuel-based production, bio-methanol production costs are 1.5-4.0 times higher. It is expected that until the costs of biomass gasification come down, early

7 Excluding some low cost estimates of € 30-75 per tonne for natural gas (at around 3,000 kt/yr; Sarkar et al., 2011 and Intille, 2003) and some extremely high cost estimates for coal-based production (around €550 per tonne at 1,500-2,000 kt/yr; available in a 1979 study referenced by Sarkar et al., 2011). The first estimates are deemed extremely low and may represent very specific cases, whereas the second estimates are deemed too old (data from 1979) to be representative for the current situation.

8 Waste stream feedstocks include maize residue, forest residue, black liquor and rice straw that are produced as a by-product of another industrial process. The wood category includes studies focusing on wood production (specifically) for bio-methanol production. CO_2 refers to either atmospheric CO_2 or CO_2 captured from flue gases.

opportunities for bio-methanol will mostly be found in integrated production with other industrial processes (e.g. pulp, bio-diesel and bio-ethanol production). This is also reflected in the current commercial projects shown in Table 1.

- **Capital Costs –** The information on capital costs of bio-methanol plants under construction is summarised in Table 2. The capital cost per unit of capacity is at least 3.4 times higher than the capital cost of plants based on natural gas. A bio-methanol production facility based on CO_2 (e.g. the CRI plant in Table 2) is estimated to be about 15 times as expensive as the most economical natural gas-based facility. However, it should be noted that the CRI plant operates at a small scale and that investment costs per unit of capacity are expected to come down as the plant scales up. Larger plants (e.g. 30-40 kt/yr capacity) are estimated to have a significantly lower cost per unit of capacity. Overall, based on biochemical conversion, Bromberg & Cheng (2010) estimate that, for the same energy output, bio-methanol plants are about 1.8 times more expensive than bio-ethanol facilities.

Potential and Barriers

- **Supply and Demand Potential –** From a supply potential perspective, the current production of waste and by-products (e.g. black liquor and glycerin) amounts to about 3,550 and 39 PJ/yr, respectively (Gebart, n.d.). In principle,

Table 2 – Overview of Investment Costs for (Bio-)methanol Facilities

Company	Feed-stock	Investment costs, million USD	Capacity, kt/yr	Capital cost, USD/t/yr	Source
Chemrec	Black liquor	440	100	4,400	Chemrec, 2008
Värmlands-Metanol	Wood	540	100	5,400	Värmlands-Metanol, 2011
CRI	Flue gas CO_2	15	1.6	9,500	CRI, 2011
n.a.	Natural gas	650 – 1,300	1,000	650 – 1,300	Bromberg & Cheng, 2010

this would enable a bio-methanol production potential of 72 Mt/yr from black liquor (Ekbom et al., 2005) and 1.4-2.1 Mt/yr from glycerin (OECD/FAO, 2011; Dekker, 2008). These production potentials for waste streams are higher than the current methanol production from petrochemical feedstock (i.e. around 45 Mt/yr). The glycerin market is currently depressed because the increasing bio-diesel production has led to a significant glycerin oversupply, with glycerin prices dropping from about €1,600/t in 2003 (Rupilius & Ahmad, 2004) to about €590-700/t in June 2011 (ISIS, 2011). The lower price makes the feedstock more economical for bio-methanol production. Furthermore, the current global coal gasification capacity amounts to about 9.0 Mt of methanol, with an increasing trend, mostly in China (Wang, 2009). This gasification capacity could in principle be (co-)fed with biomass to produce bio-methanol. In reality, these methanol supply potentials could be difficult to exploit. For example, black liquor is already currently used in recovery boilers in pulp mills for its high energy content (Ekbom et al., 2005) and bio-methanol production should thus compete with the current use. Similarly, if new uses for glycerin are found, this could lead to an increase in its global prices.

From a demand perspective, bio-methanol can be used to replace petrochemical methanol (45 Mt/yr produced in 2011), but it can also be converted into ethylene (120 Mt/yr; OGJ, 2011) and propylene (65 Mt/yr; OGJ, 2011) in the MTO process or used as a replacement for gasoline (970 Mt/yr; IEA, 2008) and diesel (720 Mt/yr; IEA, 2008). To replace petrochemical ethylene and propylene through the MTO process, approximately 650 Mt/yr of bio-methanol would have been required in 2011[9] (Ren et al., 2008). For gasoline and diesel, these potentials are about 2,150 and 1,500 Mt of bio-methanol per year (based on the energy value of fuels only). The extremely large demand potential shows that the current gasification capacity is insufficient for a complete conversion to a global methanol-based economy (a concept suggested by Olah et al., 2009). Such a switch would require more gasifiers running on a variety of different feedstocks.

- **Drivers and Barriers –** Current research is focused on improving bio-methanol production and gasification of biomass sources in general, to reduce the environmental impact of the chemical industry and ensure the optimal use of

9 "Bio-methanol requirement" refers to the amount needed to replace all ethylene, although the MTO process produces propylene as well (accounting for about 18-46% of the MTO outputs; Ren et al., 2008). By meeting the total ethylene demand of 118 Mt/yr, about 148 Mt/yr of propylene would be co-produced. This is about 2.4 times higher than the current propylene demand (63 Mt/yr).

by-product streams. However, some barriers to widespread implementation exist. From a technical point of view, the biomass gasification is the most challenging step. Different gasifier concepts offer different performance, and it is unclear which one is best suited to biomass (Nouri & Tillman, 2005). The gasification efficiency is expected to improve by 5-10% through technology innovation (Bromberg & Cheng, 2010), and this could remove one of the barriers to bio-methanol production (low energy efficiency leading to higher costs). On the other hand, in the syngas-to-methanol step, the potential for efficiency improvement is limited because the process is rather well-known from experience with natural gas-based production.

Another barrier to bio-methanol commercialisation is the relatively high capital cost. This is in part due to the fact that the crude syngas produced from biomass is more contaminated compared to production from natural gas and therefore requires additional cleaning technologies (Bromberg & Cheng, 2010). However, the increased cleaning capabilities of bio-methanol facilities also allow for a greater range of feedstock inputs. Bromberg and Cheng (2010) have suggested that this makes bio-methanol facilities suitable for the gasification of municipal solid waste (MSW). Because MSW landfill disposal is costly and environmentally questionable, recycling MSW in industrial processes could generate additional income and compensate for high capital costs.

Natural gas prices could also impact the growth of bio-methanol production. The cost comparison between petrochemical- and biomass-based production will determine to what extent bio-methanol can substitute for the petrochemical route. Removing subsidies on fossil fuels, as recently recommended by the OECD (2011), could help close the price gap between methanol from natural gas and bio-methanol. However, it should be noted that methanol is increasingly produced in very large plants (over 1 Mt/yr), which offer substantial economies of scale and low production costs. Producing bio-methanol at a similar capacity will be challenging because of technical and logistical problems in gathering, storing and handling sufficient amounts of biomass feedstock (Bromberg & Cheng, 2010). Co-supply facilities using biomass and by-products (with no seasonal availability variation), as well as fossil fuel sources, could help improve the overall economics of the process.

The market development of bio-methanol will also depend on the demand for biomass for other uses (e.g. for power generation and biofuels). In this situation, new policies will be needed to determine the optimum use of the limited biomass feedstocks. While there are clear alternatives available for the power sector (e.g. photovoltaics) and the transportation sector (e.g. electric vehicles), the chemical sector will always require a source of carbon, which

can only be provided sustainably from biomass or waste streams (and partly from recycling). However, the increased use of bio-methanol as a transportation fuel could improve the economies of scale and lower the bio-methanol production costs for the chemical sector as well.

Policies to promote the use of bio-based chemicals and materials need to look at the entire life cycle of CO_2 emissions. Present policies only take the direct emissions from chemical production processes into account. Therefore, a policy framework which fully credits the environmental advantages of bio-based materials needs to be established. Such a system could make carbon tax systems more effective in promoting the production of bio-based materials. Policies could also include eco-labeling of bio-based chemicals, information campaigns and subsidies for producers (Hermann et al., 2011).

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Table 3 – Summary Tables: Key Data and Figures on Bio-methanol Production

Overview of indicative data for (bio-)methanol production from the literature					
Feedstock	**Maximum single plant capacity (kt/yr)**	**Estimated production cost[a] (EUR/t methanol)**	**Non-renewable energy use[b] (GJ/t)**	**Efficiency[c] (%)**	**Greenhouse gas emissions[d] (t CO_2 eq/t)**
Coal	220 (China)	150-300	> 35	50-60%	n.a.
Natural gas	1,900 (Trinidad & Tobago)	100-250	29-37	60-70%	0.8
Wood	400 (proposed)	160-940	n.a.	50-60%	0.6
By-product/ waste streams	200 (Netherlands) 400 (proposed)	200-500	n.a.	50-60%	0.6
CO_2	1.6 (Iceland) 40 (proposed)	500-900	n.a.	n.a.	n.a.

a) Estimates based on Figure 2.
b) Values for conventional methanol from UNIDO (2010); for bio-methanol, non-renewable energy use is highly dependent on the source of process energy (steam and electricity).
c) Biedermann et al. (2006); Hansen (2005); Bromberg & Cheng (2010). Efficiency is defined as the ratio of the process outputs to the fuel inputs (based on lower heating values).
d) Cradle-to-factory-gate emission indications from Majer and Gröngröft (2010). The value for wood refers to short rotation coppice, whereas the value for waste streams refers to logging residues.

Data projections	Typical projected international values and ranges				
Technology variant	**Coal**	**Natural gas**	**Wood**	**By-product/ waste streams**	**CO_2**
Current regional application	China	Global; major production hubs in Chile, MENA region, Russia, Trinidad & Tobago	Canada, Sweden	Netherlands, Sweden	Iceland
Global capacity	Around 90 plants globally; production of 45 million metric tonnes in 2009, with 60 million metric tonnes expected in 2015		Around 200,000 metric tonnes per year		
Lifetime/capacity factor	>25 years / 85%				
Technology expectations	Gasification efficiency is expected to improve by 5-10% through technology innovation, but only limited efficiency improvements are expected in the syngas-to-methanol step.				

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