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METHANOL

AS A MARINE FUEL

– Availability and Sea Trial Considerations

Maritime Energy and Sustainable Development (MESD) Centre of Excellence

Methanol as a Marine Fuel
– Availability and Sea Trial Considerations

This study is conducted by the Maritime Energy & Sustainable Development (MESD) Centre of Excellence in collaboration with Methanol Institute, Dongguan Transmission & Fuel Injection Technologies Co., Ltd, and China Classification Society (CCS). This study has received research funding from the Singapore Maritime Institute (SMI).

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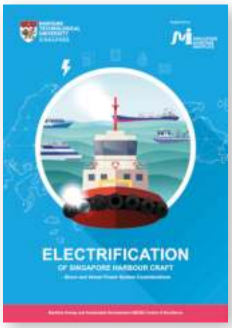

Executive Summary

The report is prepared under the collaboration between Nanyang Technological University (NTU), Methanol Institute (MI), Dongguan Transmission & Fuel Injection Technologies Co., Ltd. (FIT) and China Classification Society (CCS). This evaluation study is premised upon several high-level considerations: the availability of methanol from a global perspective; the provisions provided by marine authorities; and the experience from early adopters/pilots using methanol fuel for marine vessels.

Methanol has drawn much attention as a marine fuel due to its potential in GHG emission reduction, ease of handling, operational safety and engine compatibility. Methanol production from fossil feedstock (natural gas and coal) has reached a global scale that makes it a chemical commodity with established storage and distribution infrastructure.

Used as fuel, methanol produced from fossil feedstock emits more life cycle GHG than direct burning of fossil fuel. It is, therefore, necessary to use low carbon feedstock such as biomass and renewable energies. Using global exergy flow as the basis, the authors identify several potential pathways, which are dependent on energy from solar PV, wind, and biomass. Furthermore, a hypothetical analysis of plant productivity reveals that plant biomass has enough potential to meet the entire marine energy demand in the next few decades. In Southeast Asia where biomass feedstock is abundant, a methanol pathway from this feedstock can be more favourable. The study also highlights that future unlimited methanol production relies on direct carbon capture from the air, with hydrogen generated from wind energy or solar PV. However, this technology has a high production cost and capital investment.

The study identifies bunker tankers as an early adopter using methanol powered system on board, taking into consideration of several regulatory provisions, which include IGF code, CCC (Carriage of Cargoes and Containers) guidelines, and references from chemical cargo handling guidelines. The recommendation is also based on case studies of the two pioneering installations: Green Pilot and Stena Germanica.

The study also presents a general observation on methanol engine retrofit. Several concepts have been implemented, such as changing ignition mechanism, adding combustion improver and using pilot fuel injection. All these approaches address the less than satisfactory ignition property of methanol.

The study prescribes the recommendations and considerations when preparing for a sea trial. A sea trial checklist is proposed and needs to be prepared in advance as per the vessel's specification and operating profile. These listed pre-trial tests and requirements will need approval from a recognised marine classification society.

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B20	A blend of 20% biodiesel and 80% petroleum diesel
B30	A blend of 30% biodiesel and 70% petroleum diesel
B100	Pure biodiesel without petroleum diesel blend
CCC	Carriage of Cargoes and Containers
CCS	China Classification Society
CCU	Carbon Capture and Utilization
CI	Compression Ignition
CNG	Compressed Natural Gas
COPT	Core Oil Palm Trunk
CO_2	Carbon Dioxide
CRI	Carbon Recycling International
DAC	Direct Air Capture
DF	Dual Fuel
DME	Dimethyl Ether
ECU	Engine Control Unit
EFB	Empty Fruit Bunches
EGR	Exhaust Gas Recirculation
ESD	Emergency Shut Down
EU	European Union
FAME	Fatty Acid Methyl Esters
FID	Final Investment Decision
FIT	Fuel Injection Technologies
GHG	Greenhouse Gas
GPP	Gross Primary Productivity
GWP	Global Warming Potential
HAZID	Hazard Identification
HFO	Heavy Fuel Oil
HVO	Hydrotreated Vegetable Oil
H_2	Hydrogen
ICE	Internal Combustion Engine
IGC Code	International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF Code	International Code of Safety for Ship Using Gases or Other Low-Flash Fuels
IMDG	International Maritime Dangerous Goods
IMO	International Maritime Organization
IMSBC Code	International Maritime Solid Bulk Cargoes Code
LEL	Lower Explosion Limit
LHV	Lower Heating Value
LH2	Liquid Hydrogen
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LSHFO	Low Sulphur Heavy Fuel Oil
LUC	Land Use Change
MDO	Marine Diesel Oil
MESD	Maritime Energy and Sustainable Development Centre of Excellence
MGO	Marine Gas Oil
MI	Methanol Institute
MPA	Maritime and Port Authority of Singapore
MSC	Maritime Safety Committee
MTBE	Methyl Tertiary Butyl Ether
MTO	Methanol To Olefin
NO_x	Nitrogen Oxides
NTU	Nanyang Technological University
OPEFB	Oil Palm Empty Fruit Branch
OPF	Oil Palm Fronds
PM	Particulate Matter
POX	Partial Oxidation
PV	Photovoltaic
SCR	Selective Catalytic Reduction
SDS	Safety Data Sheet
SFOC	Specific Fuel Oil Consumption
SI	Spark Ignition
SOLAS	International Convention for the Safety of Life at Sea
SO_x	Sulphur Oxides
SVO	Straight Vegetable Oil
TRL	Technology Readiness Level

1

Introduction of Methanol as a Fuel

This study to evaluate the potential use of methanol as a marine fuel is a result from the collaboration between Nanyang Technological University (NTU), Methanol Institute (MI), Dongguan Transmission & Fuel Injection Technologies Co., Ltd. (FIT) and China Classification Society (CCS). The study provides a high-level understanding of the availability of methanol as a marine fuel, and the critical considerations before a sea trial is conducted.

1.1 General Properties of Methanol

Methanol (CH_3OH) is the simplest form of alcohol. It is a light, volatile, colourless, flammable liquid with a distinctive odour at room temperature and pressure. Methanol has been used widely as a chemical for various industrial and domestic applications. Recently, methanol is increasingly being considered an alternative fuel to reduce greenhouse gases and pollutants' emission [1].

Methanol burns with only water and carbon dioxide as by-products when combustion is complete. Methanol is an oxygen-rich fuel that combusts in an ICE (Internal Combustion Engine) emitting no sulphur oxides (SO_x), a negligible amount of particulate matter (PM) and nitrogen oxides (NO_x). The emission factor of methanol is listed in table 1.1, as a comparison to conventional marine fuels and several other alternative fuels.

There is no global warming potential from methanol slip because it degrades rapidly in air and groundwater as a result of a photochemical reaction or bacterial digestion. The chronic toxicity due to occupational contact of methanol is very low. It has been reported that skin contact with high concentrations of methanol has been effectively cured with the proper treatment using ethanol [6].

Fuel	Energy Convertor TRL[a]	Calorific Value[b]	SFOC	Operational Fuel Emission Factor (g/kWh)					
		MJ/kg	g/kWh	CO_2	CH_4	N_2O	SO_x	NO_x	PM
LSHFO	9	40.5	179	541	0.01	0.027	3.23	15.8	0.72
MDO	9	42.6	170	524	0.01	0.026	0.32	14.8	0.16
LNG	9	48.6	150	412	3	0.016	0.003	1.17	0.027
LH2	3 ~ 4	120	57	0	0	0	0	0	0
Methanol	**8 ~ 9**	**20**	**381**	**522**	**0**	**0**	**0**	**3.05**	**0**
Ammonia	6	18.9	381[c]	0	0	N.A.	0	N.A.	0
SVO Soy	7 ~ 8	37.5	195	-	0.0064	0.013	0.37	17.1	0.19
Biodiesel Soy	9	37.8	187	-	0.0061	0.013	0.36	17.9	0.18
HVO	9	44.1[3]	164[d]	-	-	-	-	-	-

Table 1.1 Comparison of fuel emission factors [2]

[a] Technology Readiness Level
[b] Lower heating value
[c] Calculated value [3]
[d] Calculated from lower heating value

It is worth mentioning that the incomplete combustion of methanol produces formaldehyde - a carcinogenic pollutant. The formaldehyde formation is caused by the presence of the engine's internal crevices, cold spots, and fuel leakages. However, in high-pressure diesel cycle engines, the formaldehyde emission is of lesser concern. There is no fuel slip and all the methanol is burned at high temperatures (1,300 degree Celsius) which does not favour the formation of formaldehyde [4].

1.2 Life Cycle GHG Emission

When produced from renewable resources, methanol offers the potential to reduce the overall greenhouse gas and pollutants emission associated with its lifecycle. In biomass rich Southeast Asia, there is an abundant supply of renewable feedstock such as the waste streams from agricultural industry or forestry residuals. These are considered the future low carbon sources for methanol production.

In order to carry out a GHG emission life cycle assessment, MESD narrowed down the feedstock to the methanol production pathway to oil palm fronds (OPF), a by-product from oil palm plantation. As a comparison, a biogas conversion pathway is used, starting from the empty fruit bunches (EFB) as the feedstock. The LCA results (table 1.2) shows that the GHG emission of methanol produced from OPF is lower than that of fossil methanol, biogas from EFB and biodiesel from the same plantation.

Fuels	CO_2-eq (g/MJ)	CO_2-eq (g/kWh)		Engine Efficiency (%)[a]	Remarks	Reference
	Well-to-Tank	Tank-to-Propeller	Well-to-Propeller			
LNG (fossil)	18.5	488 ~ 549	630 ~ 691	47 (Otto SI) (155.8 g/kW h)[b]	Well-to-tank refers to gas well to LNG bunker barge	[5]
LNG (biogas)	55.4	107	531		EFB fermentation, and the waste residual returns to land as fertiliser	[6]
Biodiesel	10.29	4.1	84.6	46 (Diesel [13]) (184.7 g/kW h)	From palm oil, FAME as the end product, without considering LUC (Land Use Change)	[7]
	52.1 ~ 148.8	4.1	412 ~ 1,167		With LUC (11 ~ 42 years for carbon payback). CO_2-eq emission is 1,969 to 5,626 kg/(tonne.year) of biodiesel	[8]
Full-electric (Singapore grid)	N.A.	N.A.	736	73% for electric power transmission	Does not include the 2nd life of battery	[9]
	N.A.	N.A.	577		Exclude GHG of battery production	[9]
Methanol (natural gas)	27	550	766	45	N.A.	[10]
Methanol (biomass)	42.2	0	338	45	Produced from OPF (oil palm fronds) originally used as fertilisers, electricity is from Malaysian grid	[11]

Table 1.2 Comparison of well-to-propeller GHG emissions of fuels

[a] High speed engine except for full-electric option

[b] Methane slip and N_2O emission is 3g/kWh and 0.016 g/kWh, respectively

The lower LCA GHG emission of methanol (from OPF) can be expected due to the following reasons.

a. Methanol does not show global warming potential (GWP) from fuel slip, where it can be a major concern with methane-based fuels (LNG, biogas).
b. A high energy conversion yield from the raw feedstock to methanol is achievable, making the methanol pathway more energy efficient.

1.3 Methanol Fuelled Ships

Commercial Fleet

By the end of 2019, there were 10 ships running on methanol fuel and two ships being built (table 1.3). Besides a RoPax ship (Stena Germanica) powered by medium speed 4-stroke engines, the rest 11 ships are powered by 2-stroke low-speed engines, consuming their cargo (methanol) as fuel.

Development Projects

There are a number of pilot projects evaluating the various options for the adoption of methanol as a marine fuel. The development is summarised in table 1.4. Unlike the commercial fleet cases, a significant portion of these projects start with retrofitting smaller engines, or with the disruptive concept to enhance GHG reduction.

Vessel Name	Company	Vessel Type	Ignition Type	Engine Power (kW)	DWT (tonne)	Remarks	Reference
Mari Couva	NYK	Oil / Chemical Tanker	CI, slow speed, 2 stroke	7,180	49,000	New Build	[12] [13]
Mari Kokako	IINO Kaiun Kaisha & Mitsui	Oil / Chemical Tanker	CI, slow speed, 2 stroke	7,180	49,000	New Build	[12] [13]
Lindanger	Waterfront Shipping	Oil / Chemical Tanker	CI, slow speed, 2 stroke	10,320	49,999	New Build	[14] [15]
Leikanger	Waterfront Shipping	Oil / Chemical Tanker	CI, slow speed, 2 stroke	10,320	49,999	New Build	[14] [16]
Mari Jone	Marinvest	Oil / Chemical Tanker	CI, slow speed, 2 stroke	7,580	49,999	New Build	[17]
Mari Boyle	Marinvest	Oil / Chemical Tanker	CI, slow speed, 2 stroke	7,580	49,999	New Build	[17]
Taranaki Sun	MOL	Oil / Chemical Tanker	CI, slow speed, 2 stroke	8,470	49,994	New Build	[18] [19]
Manchac Sun	MOL	Oil / Chemical Tanker	CI, slow speed, 2 stroke	8,470	49,994	New Build	[18] [20]
Cajun Sun	MOL	Oil / Chemical Tanker	CI, slow speed, 2 stroke	8,470	49,994	New Build	[18] [21]
N.A.	Proman Stena Bulk	N.A. (built in Guangzhou)	Dual fuel (12,500 tonnes/year, fuel consumption)	N.A.	49,900	New Build	[22]
N.A.	Proman Stena Bulk	N.A. (built in Guangzhou)	Dual fuel (12,500 tonnes/year, fuel consumption)	N.A.	49,900	New Build	[22]
Stena Germanica	Stena Lines	RO-Pax	CI, 4 stroke, medium speed	23,000	10,670	Retrofit	[23] [24]

Table 1.3 Methanol powered ocean-going ships

Project/ Vessel Name	Company	Vessel Type	Engine Type	Engine Power (kW)	Gross Tonnage	Remarks	Reference
Pilot 729 SE	ScandiNAOS	Pilot boat	SI, high speed (CNG convert) (CI convert)	313	20	Retrofit	[25]
Jupiter	-	Road ferry	SI, high speed	1,324	737	Retrofit	[26]
Leanship	Volvo Penta	-	High-speed dual fuel on methanol	-	-	Retrofit	[27]
Methaship	Caterpillar, MAN etc.	Cruise Ropax Ferry	Medium speed	-	-	-	[27]
Green Marine Methanol	A consortium of 22 companies	Total 9 ships including new build and retrofit	-	1,000 ~ 12,000	300 ~23,000 (DWT)	Methanol is from carbon neutral sources	[28]
The HyMethShip	-	-	Hydrogen ICE with methanol converter and CCS	-	-	Claims 97% CO_2 reduction	[29]

Table 1.4 Other completed, ongoing and upcoming methanol projects

2 Methanol Fuel Production and Supply

2.1 Global Production and Consumption

Methanol is either produced from fossil fuels or biomass. Current methanol production from mega plants around the world is using fossil-based natural gas and coal as their feedstock. There are over 90 methanol plants with a combined production capacity of around 110 million tonnes [30]. As of 2016, Methanex was the largest methanol producer in the world, contributing to 14% of the market share [31]. According to IHS, global methanol demand reached 75 million metric tonnes in 2015 (24 billion gallons or 91 billion litres), driven in large part by MTO and emerging energy applications, which has accounted for up to 46% of methanol consumption. The recent IHS study has revealed the demand growth through the statistics in 2018 [31]. Besides the conventional use for chemical production on formaldehyde (29%) and acetic acid (9%), the energy-related methanol consumption including direct fuel use (10%), MTBE (12%), DME (5%) and Biodiesel (4%) accounted for 31% of methanol use, of which the China market had a dominating share (57%) of the total consumption [31]. The further breakdown of methanol's energy use is shown in figure 2.1, in which methanol is either burned directly or converted into forms that can be "drop-in" fuels for existing internal combustion engines.

Eventually, the availability of methanol fuel is determined by the abundance of feedstock. Fossil resources (coal and natural gas) will continue to dominate the feedstock supply for methanol production for a long time. Renewable feedstock such as biomass, captured carbon dioxide, and renewable hydrogen are expected to have more contribution when life cycle CO_2 emission is concerned.

2.2 Global Potential of Renewable Energy Supply

It is critical to have a top-down understanding of the flow of renewable energies, almost all of which are originated from solar radiation. The global exergy flux, reservoirs and destruction map provides an excellent global view (figure 2.2) [32]. Solar energy is abundant; there are 86,000 TW incident flow onto the lower atmosphere and 48,000 TW onto the surface, respectively. By natural process alone, there are 90 TW absorbed to feed the planet's photosynthesis, 870 TW to blow the wind [34]. In comparison, the global energy demand by human activity in 2018 was 14,301 Mtoe (table 2.1) or 19 TW year, and the demand by total shipping was 250 Mtoe or 0.332 TW year [35].

Solar energy needs to be converted into a form of "energy mass" that can act as a renewable feedstock. Natural photosynthesis is currently the most available and efficient process to capture carbon and convert it into carbohydrates, an "energy mass". In contrast, the electricity and heat from solar energy need to be converted into a form of "energy mass" to carry energy vectors such as hydrogen. However, this needs a further step using electrolysis. There are four main solar-derived energies being harnessed: solar PV (photovoltaic), solar thermal, wind and hydro. Their recent installed capacity is summarised in table 2.2, which is still a small proportion compared to the total capacity of global electricity generation of 7.72 TW [36]. Nevertheless, future large-scale renewable methanol production would require abundant renewable electricity to be readily accessible at a reasonable cost. It is worth noting that the offshore wind has a cumulative installed capacity of 0.022 TW (22GW) at the end of 2018 [37], and it can serve as a potential to produce green hydrogen, and eventually methanol.

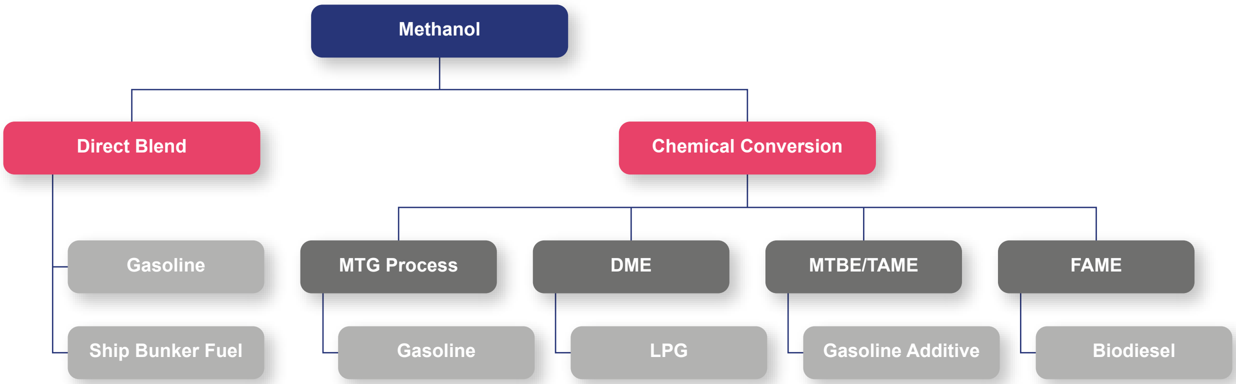

Figure 2.1 The major methanol end-users in fuels applications
Source: Adapted from [32]

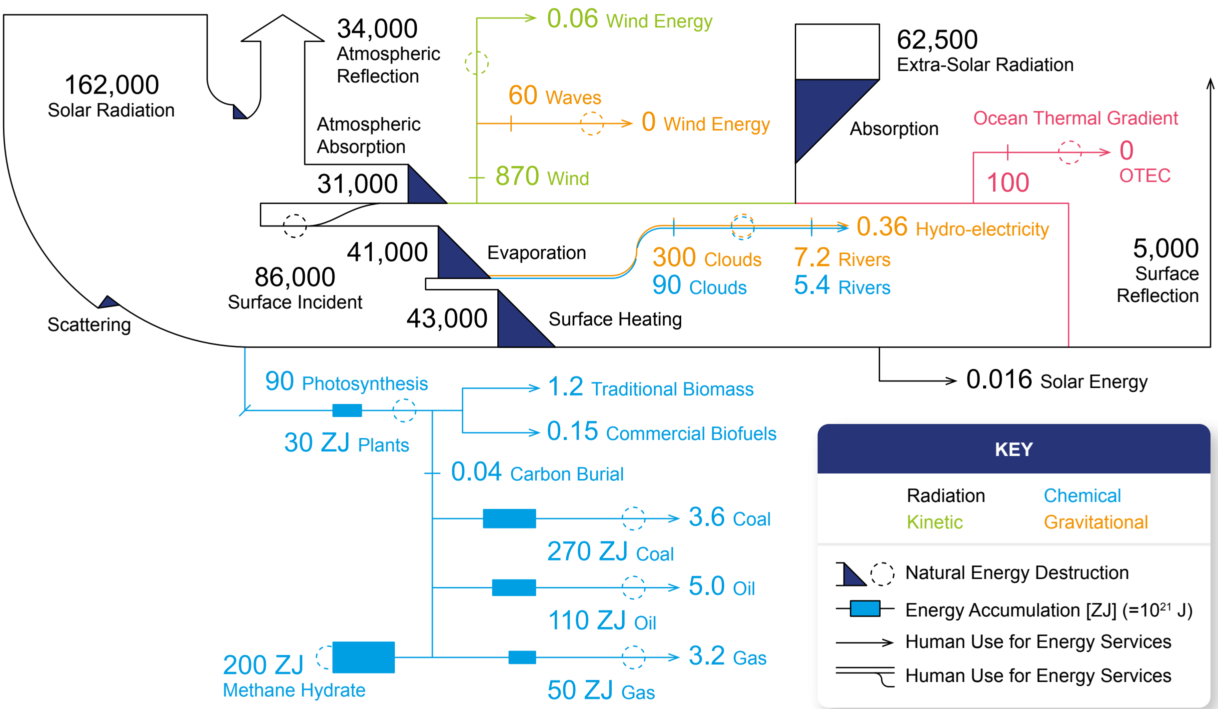

Figure 2.2 Global exergy flux, reservoirs and destruction
Source: Adapted from [33]

	Coal	Oil	Gas	Nuclear	Hydro	Biomass and Waste	Other Renewables	Total Energy Demand
Energy Demand	3,778	4,488	3,253	710	364	1,418	289	14,301

Table 2.1 World energy demand summary (Mtoe, in 2018) [38]

	Solar PV	Solar Thermal	Wind	Hydro	Total Electricity Generation
Capacity (TW)	0.398	0.472	0.600	1.267	7.72

Table 2.2 Global installed capacity of solar PV, solar thermal, wind and hydroelectric [36][39][40]

2.3 Feedstock for Methanol Production

2.3.1 Fossil Feedstock

The methanol production process from fossil resources has been developed for almost a century. Currently, methanol is produced in large quantity through a two-step catalytic process that involves: 1) gasification of carbonaceous feedstock into a gas mixture of carbon monoxide and hydrogen (syngas), and 2) converting the syngas into methanol. Coal and natural gas are used as the most available fossil feedstock to achieve good overall economics. When used as a marine fuel, the fossil-derived methanol produces higher life cycle GHG emission than conventional HFO and MGO [41] do. However, the production of fossil-based methanol is still increasing, due to the demand from the chemical industry or as the feedstock for MTO (methanol to olefin) process [42].

2.3.2 Biomass Feedstock

Biomass is an organic carbonaceous material that originates from plant photosynthesis. Out of the 90 TW exergy flow into photosynthesis globally, only 1.2 TW goes into traditional agricultural biomass and 0.15 TW into commercial biofuel production [34]. When biomass is used as a potential carbonaceous feedstock, it is important to know the land productivity of biomass production and the area of land needed to meet the needs of the maritime industry.

Biomass is produced by plants through photosynthesis. There are two main categories, C3 and C4 plants based on the differences in the carbon compounds assimilated at the beginning of the photosynthesis. The theoretical maximal photosynthetic energy conversion efficiency is 4.6% and 6% for C3 and C4 plants, respectively. However, given the fact that plants are the perennial living organism with self-standing and propagating structure, plant biomass is still considered one of the best storages of solar energy. From a global perspective, tropical terrestrial forests, savannahs and grasslands account for 60% of the total terrestrial land surface metabolism, making them the most productive area of plant biomass [43]. On the other hand, the productivity of ocean-based plant biomass is significantly less [44].

Biomass: Land Productivity and Potential

Plant species with high energy yield per unit area of land provide more biomass for methanol production. Numerous research has proposed several high-yielding candidate plants, known as energy crops. Of particular interests are the energy crops that are more related to or originates in the tropical regions.

Plant Species	Biomass Productivity (tonnes ha^{-1} year^{-1})		References
	Lignocellulose	Fatty Acid Tri-Glyceride	
Miscanthus	13 ~ 44 (dry)	-	[45]
Sugar Cane	79 (wet)[a], 21.3 (dry)	-	[46]
Oil Palm	39 ~ 40 (dry)	4 ~ 5	[47]
Pongamia	-	7 ~ 29	[48]
Creeping River Grass[b]	80	-	[49]
King Grass[c]	28 ~ 79	-	[50]

Table 2.3 Commercial and emerging plant species with high biomass productivity

[a] Water content of fresh sugar cane is 73%

[b] Echinochloa polystachya

[c] Pennisetum americanum ×P.purpureum

Taking the tropical forest as an example, the gross primary productivity (GPP) ranges between 30 and 40 Mg C ha^{-1} year^{-1}, which is affected by atmospheric carbon dioxide level [51]. A study on Indonesian plantation in rain forest reveals that 36.48 to 63.55 (dry weight) tonnes of biomass can be produced per hectare of land per year [52]. Another study on the forest of Southeast Asia found that the productivity varies greatly with tree species, Albizia produces more biomass (18.81 ton ha^{-1} year^{-1}) than Eucalyptus (11.76 ton ha^{-1} year^{-1}) [53]. Table 2.3 lists several candidate species with high productivity and adaptability to various soil and climate conditions. Miscanthus and sugar cane are well-studied grassy crops with widespread distribution in Southeast Asia. The creeping river grass and king grass are the most productive crops, being reported to produce 80 tonnes of dry biomass per hectare per year, close to the theoretical yield of C4 plants. However, the yield may drop to half or lesser under more realistic conditions due to the limit of water and nutrient supply.

From the energy perspective, there is no distinctive boundary to limit the end-use of a plant. For example, oil palm is a good producer of both oil (fatty acid triglyceride) as well as lignocellulose feedstock. Inarguably, oil palm provides the highest yield of oil per hectare per year compared to the other commercially planted oil-bearing crops. An average yield of 4 to 5 tonnes of crude oil per hectare of land with best fields giving as high as 7 to 8 tonnes of crude oil per hectare makes oil palm the most efficient oil-bearing crop in the world. In addition to the high yield of oil, the lignocellulose biomass as a byproduct of palm plantation may well be considered a future feedstock for methanol production, including OPEFB (oil palm empty fruit branch) and COPT (core oil palm trunk).

Alternatively, there will be a future scenario that both biodiesel and biomethanol are produced from the same starting energy crop, making use of the lipid and lignocellulose mass more effectively. With the progress of agricultural technology and fertiliser production, the World Bioenergy Association [54] predicts that by 2035 the global biomass potential will reach 150 EJ (or 4.76 TW year), in which 43% and 52% will come from agriculture (including energy crops) and forest respectively, the remaining 5% is from waste streams. As a result, the global biomass production's stored energy will far exceed the consumption from the total shipping of 0.332 TW year in 2018. However, there is a need to understand how biomass energy is converted into methanol for marine applications.

Biomass Conversion

Biomass conversion to methanol is one of the many options to obtain sustainable fuels. When compared to other pathways such as biodiesel, biomethane and bioethanol, the conversion to methanol is more robust and versatile. The entire biomass feedstock can be thermally broken down into syngas for methanol production, allowing a wide range of organic feedstock to be used. The reported conversion efficiencies based on dry biomass varies, from 40% to 50% in a 100 tonnes/day plant using lignocellulose feedstock [55], 45% to 57% from wood [56][57][58], and up to 44% from oil palm residuals [59].

An effective way to improve the efficiency is to add hydrogen gas directly into the biomass gasification step to optimise the reactants (hydrogen to carbon monoxide) ratio. As a result, a simulated plant integrating woody biomass and water electrolyser can achieve methanol exergy efficiency of 72%, and a total energy efficiency of 96% when waste heat is utilised [60]. The improvement also opens up the opportunity to incorporate renewable electron with biomass to achieve satisfactory methanol output if a dedicated land area is a limiting factor.

2.3.3 Non-bio Renewable Feedstock

The direct capture from the air provides an unlimited supply of carbon dioxide for methanol production. The pathway is a hydrogenation process of carbon dioxide.

$$CO_2 + 3H_2 \longleftrightarrow CH_3OH + H_2O \qquad \Delta H = -49.16\ kJ/mol$$

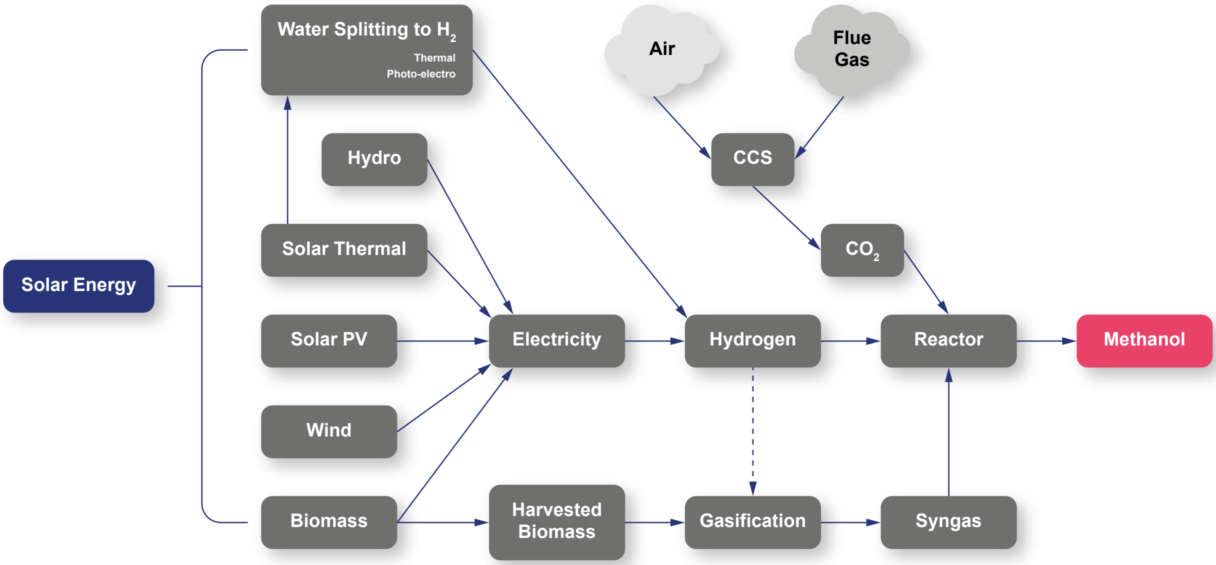

Figure 2.3 Renewable methanol production pathways

The concentration of carbon dioxide in the air is very low. Until recently, the recorded level reached 414.42 ppm from Mauna Loa Observatory, Hawaii [61]. Direct air capture (DAC) of CO_2 by conventional scrubbing process is conducted with high energy input, making the process expensive at an estimated cost of $100 to 200 for every ton of CO_2 captured [62].

Despite the gaps, carbon capture and hydrogenation are promising pathways to produce methanol offshore, where wind-generated electricity can be more readily available. As a summary, the overall scheme to convert solar energy into methanol through various main pathways is given in figure 2.3.

2.4 Economics of Methanol Production from Biomass and Renewables

At present, methanol production from renewable feedstock is more costly than that from fossil feedstock. Techno-economic analysis has been used to understand the feasibility of methanol production from biomass and other renewables. In table 2.4, the production cost of methanol from various biomass and renewable sources is provided. A comparison of the capital investment is listed in table 2.5. It was found that the price of electricity and biomass [63], the capital cost of the plant and the production capacity are primary factors that impact production cost of methanol [64] [65]. Where lignocellulose is the feedstock, several studies have indicated the cost of methanol to be around $20 per GJ [60] [63] [64] [65] [66] [67]. Methanol produced from carbon capture and hydrogenation was the most expensive at $33.8 per GJ [60]. When compared with the price of fossil-based methanol that falls within the range of $16.7 to 23.1 per GJ in 2010, it is challenging to justify the cost of bio and renewable methanol.

Feedstock	Conversion Process	Capacity (tonnes/day)	Cost Year	Production Cost ($/GJ)	References	Fossil Methanol Price ($/GJ)[d]
Forest Residue	SilvaGas process	2,000	2008	14.48	[66]	16.7 ~ 41.8 ($333 ~ 832/tonne)
Forest Residue	RENUGAS process	2,000	2008	22.67	[66]	16.7 ~ 41.8
Maize Residue	Gasification	18.8 ~ 3,792 (400 ~ 2,000 MW)	2008	21.6 ~ 29.5	[64]	16.7 ~ 41.8
Pine Wood	Gasification	2,400	2012	~ 20	[65]	22.1 ~ 24.2 ($439 ~ 482)
Wood	Gasification and water electrolysis	890 (10.3 kg/s)	2010	18.7 (€14)[b]	[60]	16.7 ~ 23.1 ($333 ~ 459/tonne)
CO_2 and Hydrogen	CO_2 capture from power plant hydrogenated with H_2 from water electrolyser	890 (10.3 kg/s)	2010	33.8 (€25.3)[b]	[60]	16.7 ~ 23.1
Animal Manure	Biogas upgrading and water electrolysis	2.85 (Farm scale)	2010	34.52 (687.03/ tonne)	[67]	16.7 ~ 23.1
Animal Manure	Biogas upgrading and water electrolysis	59.3 (Large scale POX)	2010	21.03 (418.56/ tonne)	[67]	16.7 ~ 23.1
Animal Manure	Biogas upgrading and water electrolysis	37.1 (Large scale steam reforming)	2010	22.74 (452.57/ tonne)	[67]	16.7 ~ 23.1
Wood	Gasification and water electrolysis (20% wind penetration)	1,053	2010	19.6 (USD 120 per barrel equivalent)[c]	[63]	16.7 ~ 23.1
Wood	Gasification and water electrolysis (50% wind penetration)	1,053	2025	23.0 (USD 141 per barrel equivalent)[c]	[63]	N.A.

Table 2.4 Comparison of biomethanol production cost from various techno-economic studies[a]

[a] Density and LHV (lower heating value) of methanol is 0.791 kg/litre and 19.9 MJ/kg, respectively

[b] One US dollar = 0.7472 Euro on 31st Dec 2010

[c] One barrel of oil equivalent = 6.118 GJ

[d] Methanex monthly average regional posted contract price history (non-discounted)

Company	Feedstock	Investment Cost (million USD)	Capacity (kilotonnes/ year)	Capital Cost (USD/(tonne. year))	Source
Chemrec	Black liquor	440	100	4,400	Chemrec 2008
Värmsland Methanol	Wood	540	100	5,400	Värmsland Methanol, 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

Table 2.5 Overview of investment cost for (bio-) methanol facilities [68]

Future implementation of large capacity plants will create challenges on biomass collection and logistics due to their primary production's highly dispersed nature. However, it is proposed that future opportunities may arise from distributed or decentralised smaller scale production facilities [65]. The rural production of methanol can be encouraged due to its positive social effect [64].

2.5 Other Alternative Biomass Conversion Routes

Besides the biomass-to-methanol option, bioethanol and biogas conversion routes are worth considering due to their established production technology and broad applications.

2.5.1 Bioethanol

Bioethanol can be produced from woody material as feedstock. Instead of using a high-temperature catalytic conversion, the established process relies on hydrolysis to break down the lignocellulose and starch into small sugar molecules, followed by fermentation to produce ethanol. An early study in the 1990s [69] compared ethanol and methanol production from corn, wood and natural gas. It was reported that three times as much methanol could be made from renewable raw materials than ethanol for the same amount of energy used. They also noted that methanol production from wood consumed less fossil energy than ethanol from corn. They predicted that using wood as a feedstock for methanol production would be a more attractive option. A more recent study using woody biomass came out with similar finding. One metric ton of woody biomass with 41.4% cellulose, 28.1% hemicellulose and 30.5% lignin (dry basis) can produce 290 litres of ethanol or 530 litres of methanol. The energy and carbon conversion of biomethanol production is about 30% higher than bioethanol production [70].

2.5.2 Biogas

Modern-day use of biomass usually starts from gasification to break down bulky plant tissue into small molecules by either thermal treatment or anaerobic digestion in the presence of bacteria. The product from thermal gasification is a mixture rich in hydrogen, carbon monoxide and carbon dioxide, which is a versatile precursor to produce a number of gaseous and liquid fuels. However, the fermentation process produces a gas mixture of mainly methane and carbon dioxide, or under a controlled condition with a significant amount of hydrogen [71].

The gasified biomass can be used in the gaseous form such as cleaned bio syn-gas, bio-methane or bio-hydrogen; or further catalytic conversion to produce liquid fuels. However, deeper processing is always associated with further energy loss from the raw biomass input, a conversion route with lesser steps is preferred.

Converting lignocellulose biomass into methane and hydrogen are considered alternative routes. Biomethane from either anaerobic digestion or biomass gasification exhibits similar efficiencies (62 ~ 65%) in retaining the energy from raw forest residues [72]. In a study when fermentation is used to produce bio-methane, the average productivity of 4,000 Nm^3 ha^{-1} $year^{-1}$ is used to estimate across EU-25 agricultural area, and some good individual examples reached 7,500 ~ 10,200 Nm^3 ha^{-1} $year^{-1}$ on maize plantation [73]. The bio-methane pathway shows a competitive energy yield as compared to methanol route.

Gasification to hydrogen follows a similar process. High-temperature thermochemical conversion is currently the predominant pathway due to its established process understanding and equipment design. The yield of hydrogen on a dry biomass weight basis is relatively low, with reported values varying from 8 ~ 13% via steam gasification of sawdust [74], or 12.6 ~ 17.1% from pyrolysis oil [75]. Practical issues such as gasifier design, cost of biomass, hydrogen storage and distribution infrastructure are still the main barriers that make hydrogen less competitive to methanol in the short term. However, from a long-term perspective, hydrogen produced from biomass gasification will play a key role during the transition towards a clean and sustainable energy future [76].

2.5.3 Comparative Analysis with Other Energy Conversion Routes

Table 2.6 provides a comparison between several discussed biofuels from various mainstream biomass and conversion processes. The energy yield of biomethanol route shows the broadest range with the potential to be the top producer, followed by biomethane, bioethanol and oil crop extraction. The last two routes have been well established with less room for further improvement.

In tropical regions, the average potential to produce methanol from energy crop can reach 16 tonnes ha^{-1} year^{-1}, taking the high side productivity of miscanthus as an example. Suppose methanol is to replace 50% of world bunker demand. In that case, it will require a global production of 362.5 million tonnes, or 22.6 million hectares of dedicated land use, or 0.47% of the total agricultural land on earth [77]. As a medium-term projection, it has been estimated that about 240 million ha of land, can be used for dedicated energy crops by 2035. There will be enough land worldwide to feed 9 billion people and produce more biomass for energy and material use [54].

End Product	Methanol	Methane	Ethanol	Raw Oil
LHV (MJ/kg)	19.9	50	26.8	37.2
Energy Crop	Miscanthus	Maize	Sugar cane	Oil palm
Main Process	Gasification + catalytic conversion	Anaerobic digestion	Fermentation	Extraction
Yield of Product (kg/(ha.year))	6,500 ~ 22,000[a]	5,355 ~ 7,283[b]	4,270 [78] ~ 8,258 [46]	4,500[c]
Energy Yield (GJ/(ha.year))	129 ~ 438	268 ~ 364	114 ~ 221	~ 167

Table 2.6 Energy yield of biomass conversion routes

[a] Overall 50% conversion

[b] Data taken from reference [73]

[c] Average taken from reference [47]

2.6 Methanol Production Plants Using Renewables

The list of methanol plants is shown in table 2.7. In terms of capacity, these are small plants as compared to fossil methanol plants with capacities easily reaching several millions of metric tonnes per year. Renewable methanol production relies heavily on the availability of biomass and other forms of renewables supply. An efficient (cost and carbon footprint) biomass collection network is critical. At present, there is no reported renewable methanol plant in Southeast Asia. However, as a region abundant in biomass output, Southeast Asia has enormous potential to supply renewable materials for methanol production. It is anticipated that well-selected energy crops and biomass waste stream would be the future feedstock for biomethanol in the region.

Location	Company or Project	Start-up Year	Capacity	Feedstock	Ref.
Operational					
USA	Smithfield BioEnergy	2003 ~ 2008	7,000 gallons/day (21 tonnes/day)	Swine manure	[79]
Iceland	Carbon Recycling International[a]	2011	4,000 tonnes/year	Flue gas CO_2 and H_2 from water electrolysis	[80]
Niederaussem, Germany	MefCO_2	2014	1 tonnes/day	Flue gas CO_2	[81]
Sweden	BioDME	2008	4 tonnes/day DME	Black liquor	[82]
Canada	Enerkem	2016	38 million litre/year (30,096 tonnes/year)	Municipal waste (100,000 tonnes/year, dry)	[83]
Canada	Alberta Pacific	2011	N.A.	Wood	[84]
Sweden	Chemrec Piteå	2011 ~ 2016	70 MW MeOH output from 100 MW biomass[b]	Black liquor	[85]
Sweden	Varmlands Methanol AB	late 2015	300 tonnes/day (or 90,000 tonnes/year)	Forest residual	[86]
Under Construction/Order/Proposed					
Sweden	Södra	2019	5,000 tonnes/year	Off gas of condensates from Kraft mill	[87]
Netherlands	FReSMe	2017	N.A.	CO_2 and H_2 from a steel production plant	[88]
Netherlands	Enerkem	FID (final investment decision)	270 million litre/year (213,840 tonnes/year)	Municipal, industrial, commercial and institutional waste (360 kilotonnes)	[83]
Spain	Enerkem	FID	270 million litre/year (213,840 tonnes/year)	Municipal, industrial, commercial and institutional waste (400 kilotonnes)	[83]
Europe and China	CirclEnergy	Awarded in 2019	N.A.	CO_2 from flue gas and H_2 from electrolysis	[89]
Netherlands	BioMCN	late 2019	19,636 tonnes/year	CO_2 and green hydrogen	[90]
Netherlands	Woodspirit[c]	Awarded in 2012	N.A.	Biomass	[91]
Poland	PKE & ZAK	2015	Up to 550 kilotonnes/year	Up to 10% biomass and coal	[92][d]
Germany	DeBioM	N.A.	N.A.	Wood	[92]
USA	Maverick Synfuels	N.A.	3,000 ~ 10,000 gallons/day (9 ~ 30 tonnes/day)	Natural gas or biogas	[93]

Table 2.7 Current bio and renewable methanol production projects and facilities

[a] Aka George Olah Renewable Methanol Plant

[b] Around 304 tonnes/day

[c] A consortium consisting of BioMCN, Siemens, Linde, and Visser & Smit Hanab

[d] Requote from the publication instead of the original link that is invalid

2.7 Future Methanol Production

The future production of methanol can harness the abundant supply of CO_2 from the air and hydrogen through electrolysis of water. The concept is not new but still challenging due to the difficulty of direct air capture of CO_2 and energy-intensive process to produce hydrogen by electrolysis. Energy-efficient options are described below.

Nuclear

Decades ago, it was proposed to use thermal nuclear energy to power the process [94] [95]. As a result of optimisation, carbon dioxide captured from the air by diluted potassium carbonate solution to produce potassium bicarbonate is found to require the least amount of energy. The total energy required for methanol synthesis from these sources of carbon dioxide is 3.90 kWh(e)/1b methanol, of which 90% of the electricity is consumed for the generation of hydrogen.

Offshore Solar PV

An interesting concept was recently proposed to use solar energy to recycle atmospheric CO_2 into liquid fuel. The concept is based on clusters of marine-based floating islands. Photovoltaic cells can be installed to convert sunlight into electrical energy to produce H_2 and extract CO_2 from seawater. The two gases are then reacted to form methanol, which is conveniently shipped to the end consumers [96].

The outcome of the idea is a clustered solar methanol island. It has been proposed that an individual facility is a cluster of 70 flexible PV islands, each with a diameter of 100 m (total PV area 550,000 m^2) that occupies a total area of about 1km^2 [96]. The facility's yearly output is estimated to be 15,300 tonnes/year, which is scheduled for collection by tanker ships.

Wind

The energy yield of renewables is critical. Given the same land area, wind energy has the highest yield compared to solar PV, hydroelectric and photosynthesis, making it a preferable choice for renewable methanol production (figure 2.4) [97]. Based on wind energy input, several emerging projects and concepts are summarised in table 2.8, using methanol as the energy carrier product. A schematic flow diagram is further illustrated in figure 2.5, in which methanol is considered the best energy carrier if all CO_2 is captured and recycled back to the production loop [98].

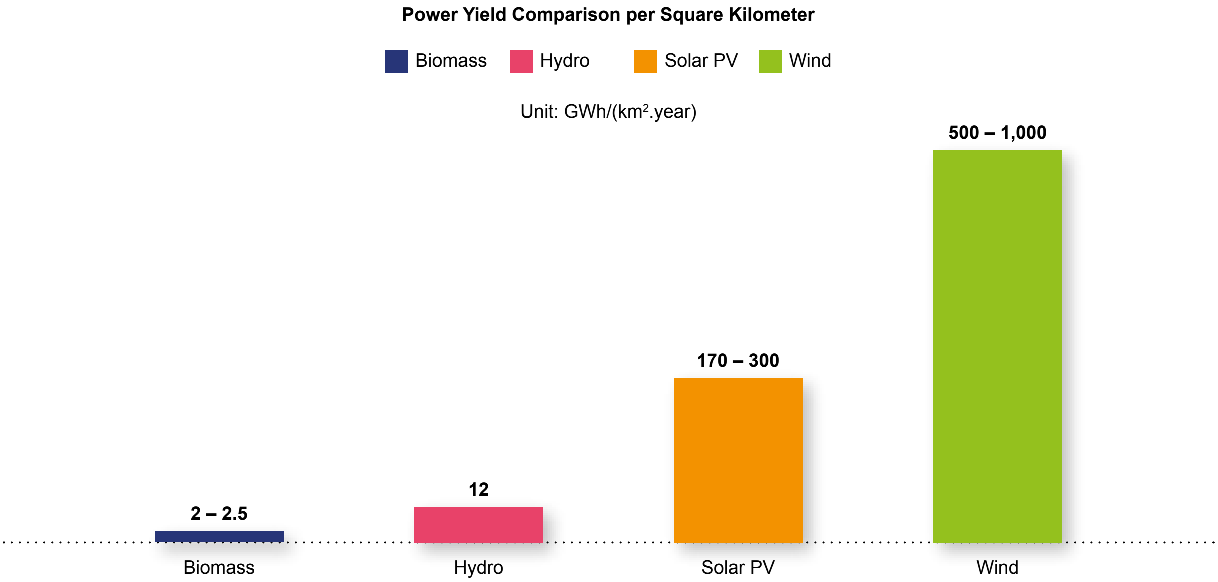

Figure 2.4 Comparison of power yield from various renewable sources
Source: Adapted from [97]

Location	Project	Commencement	Capacity	Feedstock	Reference
Sweden	Liquid wind	2019	5,000 kg/hour	CO_2 from CCU H_2 from electrolysis	[99]
Germany	Westküste 100	2030	700 MW H_2 input	CO_2 from cement plant H_2 from electrolysis	[100]
France	Farwind	2017 ~ 2020	Scenario-based	CO_2 from land supply H_2 from electrolysis	[98]

Table 2.8 Examples of methanol projects from wind energy

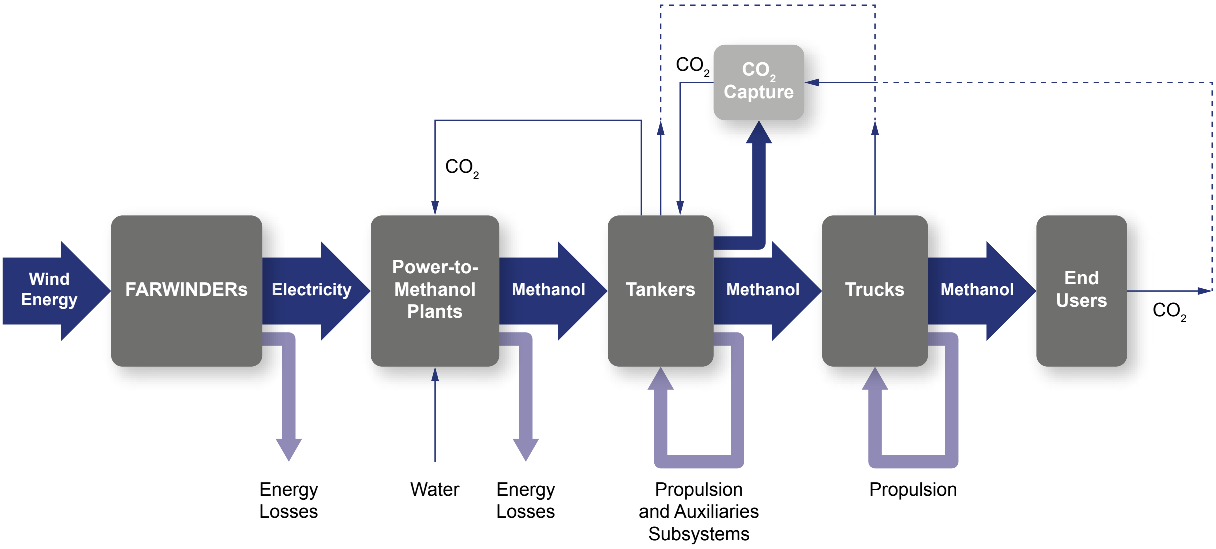

Figure 2.5 Flow diagram of the FARWIND energy system
Source: Adapted from [98]

3 Methanol Fuel Guidelines

Unlike most hydrocarbon fuels consisting of multi-components, methanol is a single-component fuel, exhibiting a set of consistent chemical-physical properties. Guidelines regulating the use of methanol as a marine fuel are still being developed.

3.1 IGF Code and CCC

The International Code of Safety for Ships using Gases or other Low-flashpoint Fuels, known as IGF Code, regulates the implementation of alternative fuels for ships. It entered into force on 1 January 2017 [101]. The objective of the code is to minimise the risk to ships, crews and the environment. The low-flashpoint fuels shall be adopted with mandatory measures for arranging, installing, controlling, and monitoring machinery, equipment and systems. The IGF code was initially limited to liquefied natural gas (LNG) [102]. To keep the IGF code up-to-date, a Sub-Committee on Carriage of Cargoes and Containers (CCC) formed with the aim to review the International Codes including IGF code, IGC code and at meantime to develop guidelines relevant to other types of fuels [101][102].

The sub-committee comprises different working groups, which are attended by delegates of the member states of IMO. They are involved in research and debate by giving examples of safe design options for the use of methyl alcohol. Hazard identification (HAZID) was conducted to assess the designs during the discussion [103]. The amendment from CCC Sub-Committee is framed after detailed study and review. Till date, there are 6 sessions conducted to undertake matters related to the safety and security of cargos with low flashpoint fuels [102]. With the contribution from CCC Sub-Committee, interim guidelines for ships using methyl/ethyl alcohol as fuel were established. The guidelines address areas that need to be specially considered when using the methyl/ethyl alcohol fuel and apply to all ships indicated in Part G of SOLAS chapter 2.1 [104]. It covers the design and indicates liabilities of stakeholders, including the responsibilities during the bunkering operations. Table 3.1 summarises the codes and guidelines related to methanol fuel for marine use.

In line with international codes and CCC amendment, marine classification societies such as China Classification Society (CCS) has also developed rules and regulations for green shipping. One of the established standards is the Guidelines for Ships Using Alternative Fuels implemented on 1 December 2017 [105]. The objective of the regulation is to provide guidelines and safety provisions when alternative fuels are adopted. Currently, it focuses on methyl/ethyl alcohol fuel, fuel cell and biodiesel. The guidelines are applicable for both new build and retrofit cases. It includes but is not limited to the information in the design of shipboard equipment, bunkering infrastructures, fire safety control and alarm monitoring system. However, the guideline is only applicable for a ship in the steel structure of not less than 20 m in length. It will be a scenario-based approach for a vessel with other design, which needs further evaluation before deployment.

With respect to existing international guidelines, the challenge is that they are mainly applicable for ocean-going vessels. With respect to vessels operating within the port limit, the guidelines may be more applicable for bigger harbour craft. For example, in Singapore, some vessels under SB and ST categories (table 4.1) are designed with ocean-going capability. When actual implementation is considered for smaller harbour craft (SP and SC categories in Singapore) operating only within the port limit, function-based guidelines from respective classification societies together with risk assessment by port authorities are supposed to be a more practical approach. It helps to identify the potential risk factors arising from the use of methyl/ethyl alcohol fuels that affect personnel on board, the environment and shipboard safety. As a result, the awareness of hazards and risk with suitable measures can be established. Further consideration about the hazards associated with vessel layout, operation profile, bunkering arrangement, together with reasonably foreseeable failures, should be addressed and evaluated with acceptable techniques. Inputs from naval architect and engineering principles with a comprehensive understanding of the operational experience and field data will help enhance the contents of the document. Likewise, a provision for methanol powered local harbour craft can be established.

Regulations and Guidelines	Timeline	Objective and Descriptions	Remarks	Reference
IGF	Jan 2017	Considered a goal-based approach and used to provide an international standard for ships other than vessel covered by the IGC Code, operating with gas or low-flashpoint liquids as fuel.	Focusing initially on liquefied natural gas (LNG).	[106][107]
CCC 6	Sept 2019	The Sub-Committee keeps updated the International Maritime Solid Bulk Cargoes Code (IMSBC Code) and the International Maritime Dangerous Goods (IMDG) Code. It also keeps under review other Codes including the International Code of Safety for Ships using Gases or other Low Flashpoint Fuels (IGF Code) and the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code).	Finalised draft interim guidelines for the safety of ships using methyl/ethyl alcohol as fuel, for submission to the Maritime Safety Committee (MSC) for approval.	[102][108]
CCC 5	Sept 2018		The sub-committee agreed, in principle, to draft interim guidelines for the safety of ships using methyl/ethyl alcohol as fuel.	[102][101]
CCC 4	Sept 2017		IMSBC Code amendment developed and IMDG Code amendments finalised.	[102][109]
CCC 3	Sept 2016		The IGF Code Correspondence Group was tasked with further developing draft technical provisions for the safety of ship using methyl/ethyl alcohol as fuel.	[102][103]
CCC 2	Sept 2015		The sub-committee began developing draft text of technical provisions for the safety of ship using methyl/ethyl alcohol as fuel, for further consideration by a correspondence group.	[102][110]
CCC 1	Sept 2014		Draft international code of safety for ships using Gases or other Low flashpoint Fuels (IGF Code) agreed.	[102][111]
CCS	Dec 2017	Formulated the 'Guidelines for Ships Using Alternative Fuels' to provide technical standards for methyl/ethyl alcohol fuel, fuel cells and biodiesel fuel application on ships for emission control.	Applies to steel ships of not less than 20m in length and using methyl/ethyl.	[112]

Table 3.1 Summary of methanol fuel-related codes and guidelines for marine use[a]

[a] Update. For further information, there are two latest publications on methanol for marine fuel use, namely, "Interim guidelines for the safety of ships using methyl/ethyl alcohol as fuel (IMO MSC102, Nov 2020)" and "Bunkering Technical Reference on Methanol (by LR and MI, Sept 2020)".

3.2 Methanol as Chemical Cargo

Methanol has been used as a chemical commodity extensively. There are established documents, such as methanol safety data sheet (SDS) [113] covering hazards identification, safe handling, storage, accidental release, firefighting, first aid and environmental considerations of methanol.

The sea transportation of methanol is regulated by the International Maritime Dangerous Goods (IMDG) code. The code is applicable to all members of SOLAS [114]. The IMDG Code requires that certain provisions be followed whenever dangerous goods are shipped by sea. These provisions require good management of dangerous goods such that they are correctly and safely:

a. Classified and identified.
b. Packed.
c. Marked, labelled and placarded.
d. Documented.
e. Stowed on board the vessel.
f. Segregated from other goods with which they may react dangerously.

In addition, appropriate emergency response information must be available, and security and training requirements must be followed.

3.3 Additional References

A detailed summary of methanol safe handling manual was published by Methanol Institute in 2008 [115]. This manual is designed to be a primary resource for information on methanol specifically for its safe handling. It presents current information on methanol's properties, potential environmental and health and safety hazards, safe handling practices, emergency response procedures, product and distribution stewardship, and risk communication. The manual provides convenient access to practical information. Key facts and useful references are highlighted in the text. Additional technical data, such as methanol's chemical, physical, and thermodynamic properties, are provided in the appendices. The reference section also presents a list of scientific and technical resources for more in-depth understanding. The manual also includes Fact Sheets on many topics related to methanol's safe handling, which include methanol use as fuel, emergency response, product stewardship, and health effects.

4 Methanol as an Alternative Marine Fuel

Prior to methanol engine retrofitting and sea trial, a good understanding and preparation work is needed to find out the feasibility and the pathways for implementation. The planned approaches are as follows:

a. Review of case studies of past and ongoing methanol ship projects from developers and operators.
b. Understand the recent direction and development by the mainstream engine makers in the market.
c. List out requirements, checklists and recommendations for a ship trial.

4.1 Observations from Green Pilot Project and Stena Germanica

4.1.1 Methanol Fuel and Engine

Fuel grade methanol allows the presence of impurities such as water, DME and higher alcohols within a certain limit. In order to retrofit an engine with comparable thermodynamic efficiency to a conventional diesel engine, one may consider several modifications such as using specially formulated methanol fuel, specific fuel injection design, varied compression ratio and injection timing.

4.1.2 Green Pilot Project

The project is a retrofit of an inland pilot vessel built in 1996 of NBS Y90 Class. The hull is aluminium with a composite material superstructure. One of the two Cummings engines was replaced by a modified Weichai or Scania diesel engine to burn methanol.

The engine was modified from a pre-launched Scania diesel engine with compression ignition. The engine is rated at 350 kW at 1,800 ~ 2,100 rpm. To make it methanol compatible, the developer ScandiNAOS modified fuel injection system and re-mapped the engine ECU. The methanol fuel is blended with 5% combustion improver to ensure a reliable engine ignition.

In practice, methanol used as a fuel does not necessarily follow the chemical standard, where water content and higher alcohol contamination have stringent limits. On the other hand, fuel grade methanol may be produced with less refining steps to be more cost-effective. The IGF code may not necessarily be followed by inland water vessels because the requirements on machinery and equipment can sometimes be over specified.

The attempt to convert methanol on board into DME and use it as diesel fuel alternative minimises engine modification. However, it was found the DME conversion yield is inconsistent. Hence, it influenced later development work (Stena Germanica) to switch to direct methanol burning by ICE. Methanol is also found to corrode carbon steel over time, which affects the selection of the material for the fuel system.

4.1.3 Stena Germanica

The vessel is a ROPAX ferry operating between Kiel, Germany and Gothenburg, Sweden. The time of travel for a single voyage is 14 hours. The vessel retrofitting started in 2015, and currently, all 4 engines (6,000 kW) are converted into a DF (Dual Fuel) system. The system (compression ignition) is a high-pressure design where the main fuel is methanol, and the pilot fuel is gas oil.

Due to the lower energy density, methanol fuel requires additional storage space, which can be converted from the existing ballast water tank. Methanol fuel is delivered through long double-wall pipe systems by sets of dedicated low pressure, and high pressure pumps up to 450 bar.

Methanol bunkering is done by truck to ship transferring at shipside, with full safety provisions such as firefighting and electrical grounding. The methanol supply is sourced from various origins including biomethanol from black liquor and fossil methanol from natural gas.

4.1.4 Summary

Implementing a methanol-powered ship requires dedicated efforts from the various stakeholders, such as the shipowner, engine maker, naval architect, methanol producer, academic and government support. From the experiences of ScandiNAOS, trials start from retrofitting an existing spark-ignited or compression ignited diesel engine. The practical issues of methanol in fuel storage, fuel delivery system, engine modification and material compatibility have been studied and well-addressed at the current stage. However, in the long run, development to reduce the cost of renewable methanol is much needed, and this is a major barrier to overcome for large scale adoption.

4.2 Harbour Craft Adoption

The study is to look into the possibility of adopting methanol fuel by various type of harbour craft. References are taken from the MESD work on the energy options for Singapore harbour craft [116]. Currently, there are around 2,300 harbour craft operating within the Singapore water [117]. They are categorised into five groups with various prefixes, namely, SP, SC, SB, ST and SR shown in table 4.1.

Prefix	Definition	Function
SP	Used for the carriage of passengers	To provide in-port limit carriage of passengers.
SC	Used for the carriage of dry or packaged goods	To provide in-port limit transportation of general/breakbulk cargo in either dry or liquid form, including Ro-Ro cargo to vessels or floating platform at anchorages around Singapore.
SB	Used for the carriage in bulk of petroleum, liquefied gases, liquid chemicals, vegetable or animal oils	Under this category, most vessels are known as bunker tanker supplying fuels to ocean-going vessels that pass through Singapore. The bunker tanker is equipped with a crane near the mid-ship, attached with a long rubber hose, and two pneumatic fenders stored on-deck, to be ready for use prior to commencing any bunkering operation.
ST	Used as a tug	To provide harbour and ocean towing or escorting services around Singapore at different anchorages. A vessel with engine shaft power less than 150 kilowatts is not qualified as a tug.
SR	Used for any other purpose	To provide in-port limit service that is not the usual norm within the harbour craft industry. Harbour craft in this category is usually outfitted with specialised equipment to fulfil its specific role. They are usually used at project sites.

Table 4.1 Singapore harbour craft prefixes

Marine gas oil is the fuel used exclusively by all types of Singapore harbour craft. In order to project a possible penetration by an alternative fuel, MESD has profiled the five groups of harbour craft, and found several favourable conditions:

a. Fleet with higher portions of old ships.
b. Larger gross tonnage.
c. Smaller engine capacity.
d. Regular and fixed operating routes.

Other factors such as preparedness of engine makers and the ships' operating route/profile will also influence the decisions made. For example, engines commercially available with alternative fuel option will be a preferable choice. The engine maker's knowledge to provide technical support is also an essential consideration. With predictable and fixed routes of a ship, it will be much easier to plan or establish supporting infrastructure for alternative fuel storage and bunkering.

4.2.1 Engine Makers

High-speed and medium-speed engines are used dominantly by local harbour craft, including common brands such as MAN, Yanmar, Cummins, Daihatsu, Mitsubishi, Weichai, Niigata and Caterpillar. Their recent developments towards emission reduction are listed in table 4.2. Attempts to reduce SOx and NOx emission are the main focus. At the same time, a more gradual approach is taken to reduce carbon dioxide. It starts from fuel economy enhancement (hybrid, waste heat recovery) and incremental means (natural gas) to more substantial reduction through the use of biodiesel blends as an immediate drop-in option. Currently, few engine makers start the development of methanol engine.

Engine Maker	Alternative Fuel	Pollutant Reduction	Remarks
MAN	Biodiesel Methanol	SCR	-
Yanmar	Biodiesel (B20) Natural Gas	-	-
Cummins	Biodiesel (B20)	-	-
Daihatsu	Natural Gas	SCR	-
Mitsubishi	Natural Gas	-	Waste heat recovery
Weichai	Natural Gas Methanol (third party trial)	-	-
Niigata	Natural Gas	SCR	Hybrid (for tugboat)
Caterpillar	Biodiesel (B30) Biodiesel (B100, developing)	SCR EGR	-

Table 4.2 Engine makers' development in alternative fuel and emission reduction

4.2.2 Operating Profile

MESD has analysed the operational routes of various harbour craft. Chemical tanker, LPG carrier and tugboat (prefix SB and ST) show clear patterns. Almost all liquid cargo is handled in the western terminals by tankers; whereas tugboats typically make short and frequent trips. The profiling will help identify the preferred type of harbour craft to use methanol as fuel.

4.2.3 Considerations for Singapore Harbour Craft

In the short term, it is challenging for methanol to act as a mainstream alternative fuel due to the competition from biodiesel and the lack of compatible engines. The production of methanol from renewables still requires a significant upgrading of production technology or facility, which will bring about cost reduction. For medium to long-term perspective, the harbour craft industry's methanol adoption will increase if its production from biomass or other renewable energy can catch up. However, there are competing rivals such as advanced generations of drop-in biodiesel, biomethane, ammonia and hydrogen, and these fuels will inevitably create competitions.

The silver lining is found in SB prefixed chemical tankers or bunker tankers as these harbour craft have the convenience to use their cargo (i.e. methanol) as fuel. The adoption of methanol for other types of harbour craft (i.e. SP, SC, SR and ST), will require developments in bunkering infrastructure as well as high-speed, low-capacity methanol engines. These are expected to occur in the latter half of this century [116].

In addition to the general perception, there can be more in-depth considerations from a harbour craft owner and operator's perspective, which include:

a. Familiarity with the guidelines concerning the storage, bunkering and use of methanol. The process would require some investment in the training of harbour craft masters and crew.
b. Extent of effort to retrofit, store and use methanol on board safely.
c. Price of methanol as a marine fuel. Currently, there is still insufficient clarity on the price of methanol as a marine fuel, which is an essential part of OPEX and will erode profit margins.
d. Availability of methanol refuelling points. The diverse operating profiles of harbour craft operators necessitate the need for convenience and ease of refuelling.
e. Voluntary adoption is insufficient to drive transition unless methanol is competitive to other drop-in alternative fuels (such as biodiesel). The transition needs strong regulator support and sustained industry efforts, underpinned by financial and supply chain considerations.

4.3 Recommendation on Methanol Installation

According to vessel configurations, there are two types of onboard energy converters, the main propulsion engine and the auxiliary engine for electricity generation. The high-speed engine is the dominant type for most harbour craft in Singapore. For SB or ST harbour craft, their engine rooms are relatively spacious, and they have higher engine capacity. In this case, there are more installations of medium-speed engines. The engine types used by Singapore harbour craft is summarised in table 4.3. All engines are compression ignited regardless of the speed.

Vessel Type	Engine Types	
	Main Engine	Auxiliary Engine
SP (≤12 pax)	CI, High-Speed Engine	CI, High-Speed Engine
SP (>12 pax)	CI, High-Speed Engine	
SC	CI, High-Speed Engine	
SB	CI, Medium-Speed Engine or CI, High-Speed Engine	
ST	CI, Medium-Speed Engine or CI, High-Speed Engine	
SR	CI, High-Speed Engine	

CI: Compression Ignition

Table 4.3 Example of engine types of harbour craft

Methanol fuel blends have been used by internal combustion engine by land transportation with established experience [27]. However, the engines used are mostly spark-ignited types, which are generally known as gas engines. A different mechanism to allow methanol fuel to ignite successfully shall be developed for the compression ignited engine used by marine vessel.

It is technically possible to convert the CI engine into the SI process, although it is not common by engine developers. The retrofitting of the engine requires customised hardware and software to match the new operating cycle. For example, ScandiNAOS tested the concept of retrofitting CI engine into SI mode. The trial included conversions on the engine fuel system, intake air system, piston replacement and modification of ECU [25]. The other approach is to make the conventional CI high-speed diesel engine run on methanol directly [25]. Since the auto-ignition stability of neat methanol is poor in the conventional CI engine, methanol has to be doped with 5% ignition improver. Under further development by engine manufacturers, this type of configuration would become a feasible option for both new builds and retrofitting projects.

For larger capacity CI engine, taking Stena Germanica as an example, a dual fuel (methanol and diesel) concept is used. Methanol was used as the main fuel and ignited by a pilot fuel for sustained combustion. The operations were more flexible since the engines can run on various modes [118]. The main conversion included a change to the double-walled high-pressure fuel system and the modification of cylinder heads for methanol intake [118]. Similarly, MAN Energy Solutions launched their methanol-compatible slow-speed engines and tested on board Waterfront Shipping tankers [119][120].

The successful pilot projects provide good references for large harbour craft with high power capacity. Medium-speed engines are used by Singapore harbour craft for the propulsion of SB and ST categories. To a certain extent, the DF system has been developed for LNG powered vessels. Evolving from the existing DF system into methanol operation can be expected if the market demand increases in the future.

There are still several challenges for a successful trial of methanol operation by harbour craft. Besides engine modification, there are further considerations related to logistics, storage and safety. It is recommended to carry out more in-depth studies on harbour craft's operating profile, bunkering, risk assessment involving port authority and marine classification societies.

4.4 Considerations for Sea Trial

Vessel sea trial should be proposed based on the types of vessel modified for methanol operation. Since the vessel's design criteria and the engine systems are different, the sea trial checklists for each harbour craft category may not be the same. In general, the sea trial checklists will cover areas of testing, measurement and inspections. Machinery including hull equipment, navigation and radio devices shall be tested. Engine and vessel performance needs to be monitored during the nautical trials.

The sea trial of methanol powered harbour craft shall be arranged after the successful commissioning of essential components like bunkering facilities, inert gas system, emergency shut down (ESD), and fire and safety control. Simulation, including the safe handling of the methanol supply system and the engine operating procedures, shall be demonstrated to ensure that the operators fully understand the system and can safely proceed to shut down when an incident occurs. Safety briefing shall be conducted to identify the responsibilities of individual parties on board before the sea trial.

According to MPA's circulars to the shipping community, all newly built vessels and vessels undergoing repairs or modification at shipyards must be granted port clearance if they wish to proceed outside port limits for sea trials. The clearance could be obtained if the Shipping Division of MPA or one of the 9 recognised classification societies certifies that it is in a seaworthy state for the sea trial [121]. This requirement will also apply to larger harbour craft, which are registered and endorsed to operate beyond port waters. Nautical trials for those vessels usually consist of tests of speed, turning circle, endurance, steering gear, zig-zag testing, and crash and emergency stop test. All tests need to meet the classification requirements and be witnessed by a surveyor for certification.

The testing, however, may not be feasible for smaller vessels under categories of SP and SC. The limitation is due to the fact that the majority of those types of vessels are usually designed for short-sea route services with smaller fuel oil storage tank. The onboard methanol storage may not be sufficient to fulfil the testing criteria as bigger vessels do. Sailing to the designated location for the trial can be challenging. Thus, a yard trial shall be arranged for those vessels designed for port-limit operations with the written permission of Port Master. The yard trial shall include but not be limited to the following aspects: 1) Control and monitoring test and 2) Endurance and speed test.

Control and Monitoring Test

It refers to the function test of engine control and methanol fuel supply system under realistic conditions. A human-machine interface panel shall be installed with easy access by ship operators to monitor the parameters of the systems. Alarm indication, vapour detectors, fuel temperature and tank levels shall be visible during operation. According to CCC 5, master fuel valves of the methanol supply system shall be triggered under critical events like methanol leakage, detection of vapour in the double-walled pipe, and 40% of LEL. Under such a scenario, the methanol engine shall be automatically shut down or changed over to conventional oil fuel operation [101]. It shall be conducted during the trial to check the alarm settings and ensure the activation of the automatic control system.

Endurance and Speed Test

It shall be conducted at the vessel's maximum draft to monitor the vessel and engine performance. During the test, the engine load shall be gradually increased and maintained at each test point for a specified period. Test duration at each load point shall be sufficient to stabilise the system and allow exhaust emission profile to be fully developed. Parameters related to the methanol engine such as SFOC, exhaust gas compositions and noise level shall be recorded at ramp-up and ramp-down stages to compare with the data from the factory test or before retrofitting.

5 Conclusion

As a potential alternative fuel, methanol has drawn much attention due to its favourable properties in GHG reduction, low emission profile, ease of handling, and engine compatibility. In recent years methanol has been used increasingly as fuel by ocean-going ships and marine vessels operating within the port limit.

Methanol is produced in large scale globally from fossil feedstock as a chemical commodity. The process emits more GHG than a direct burning of fossil fuel does. Aiming to reduce life cycle GHG emission, methanol used as a fuel shall be produced from low-carbon feedstock such as biomass and renewable energy. From a global perspective, the various forms of feedstock are all derived from solar energy reaching the earth, of which solar PV, wind and biomass have the greatest potential. In Southeast Asia, where plant biomass is abundant, the feedstock from the agriculture industry, forestry or dedicated energy crops will be the main raw material for renewable methanol production. From the future perspective, direct carbon capture from the air, combined with hydrogen generation from renewable electricity will be the ultimate supply of renewable methanol.

An overview of techno-economic analysis reveals that methanol’s production cost from renewables is higher than that from fossil feedstocks. The established plants are limited by the availability of feedstock and production capacity. It is anticipated that further cost reduction of renewable methanol can be achieved through the scale of economies and the adoption of advanced technology.

The adoption of methanol fuel by a marine vessel takes into account several considerations. These include the methanol supply chain, guidelines, bunkering, engine modification and vessel’s operating profile. As a general regulatory guideline, the CCCs (CCC1 to CCC6) provide provisions for the arrangement, installation, control and monitoring of machinery, equipment and systems using methanol as a fuel.

Several successfully installations on various types of ships proved that methanol is a compatible fuel for internal combustion engines. Marine diesel engines have been converted through different concept, which includes: changing compression ignition to spark ignition; doping methanol with combustion improver; and installing pilot fuel injection system.

The adoption of methanol by the existing fleet may be limited to specific vessel types. Taking Singapore harbour craft as an example, bunker tankers can be considered an early adopter if they carry methanol as both cargo and fuel. For a medium and long-term perspective, methanol’s adoption relies on the collective efforts from methanol producers, shipowners, engine makers, bunker operators, classification societies, and authorities.

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