

## RESEARCH ARTICLE

# Methanol as a Reservoir for Hydrogen Production and Distribution

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## Abstract

Methanol is a convenient source for the hydrogen production in a distributed mode for medium to small scale production of 3-100 m<sup>3</sup>/h with a high efficiency of 60-68% in high purity of 99.999%-99,99999%; it is used to produce hydrogen in a compact and simple onsite hydrogen generator by a single reaction step at a low reaction temperature of 270°C. The simple operation of the hydrogen generation enables the methanol to play the role of hydrogen reservoir for the direct supply of hydrogen to the user any time any place in any quantity with safety and simplicity by avoiding the high cost and safety concern of hydrogen during its distribution and storage under high pressure.

**Keywords:** Onsite production of H<sub>2</sub>; Easy conversion methanol to H<sub>2</sub>; Compact reformer; Methanol reservoir; CO<sub>2</sub> emission

## Introduction

In 1869 Zénobe Gramme invented the Gramme machine for the electrolysis of water; it became a general method for the production of hydrogen [1, 2]. Current industrial efficiency of hydrogen from electrolysis stands at 4.5~5.0 kWh/Nmh or average at 4.75kWh/Nm<sup>3</sup>H<sub>2</sub> (or 57 kWh/kgH<sub>2</sub>) [3]. Besides the electrolytic process for hydrogen production, more hydrogen today is made from the steam reforming of coal, natural gas or light hydrocarbons at 700 to 900C for large scale operation [2a, 2b] or from the steam reforming reaction of methanol at 260 to 290C for the smaller scale production capacity. [3]

Today, hydrogen is made from the steam reforming of coal, fossil oil, natural gas or methanol or from the electrolysis of water. As coal and oil are phasing out from the hydrogen production due to heavy carbon pollution, hydrogen from the steam reforming of natural gas and methanol or from the electrolysis of water become the main source of hydrogen production as shown in Table 1. Of these three processes, the steam reforming of natural gas (NG) may become the major source of large-scale hydrogen production in the future due to its low cost and the abundant supply. This process requires four synthetic steps and high reaction temperature at 700-900C in four reaction steps later while the hydrogen made from the steam reforming of methanol requires only a single step at a much lower reaction temperature of 260-280C. Besides the concern of the energy consumption in the hydrogen production, there also has CO<sub>2</sub> emission during the hydrogen production in all the three processes; the emission of CO<sub>2</sub> in the electrolysis is the highest of three hydrogen processes. The CO<sub>2</sub> emission in the electrolysis of water, however, is attributed indirectly to the generation step of electricity in the upstream. In overall, the hydrogen from the steam reforming of methanol (MOH) has the lowest energy consumption and CO<sub>2</sub> emission among the current available processes for hydrogen production as shown in Table 1.

The hydrogen from the electrolysis of water is a well known historic process, unfortunately it is burdened with high energy consumption and CO<sub>2</sub> emission from electricity during its generation. This process, however, may become the preferred process in the future when the carbon efficiency in the electricity generation is improved. Today the carbon efficiency of the power generation in the major industrial countries is fairly high between 0.3 to 0.8 kg CO<sub>2</sub>/kWh except in the northern Europe where wind power is abundant and strong and the population is relatively light.

When the power is generated with low carbon pollution, say <0.2kg CO<sub>2</sub>/kWh, the hydrogen from the electrolysis may become a dominant source of hydrogen production when supply of electric power from the renewable sources becomes abundant probably in the middle of 2040. However, the large-scale central production of hydrogen, 4,000-50,000m<sup>3</sup>/h (Nm<sup>3</sup>) for the manufacture of ammonia or methanol, may still prefer the hydrogen from the steam reforming of natural gas or hydrocarbons for lower cost; in such case, the supply of natural gas and the generation of hydrogen will require a heavy investment in facility and several high temperature reaction steps. On the other hand, the steam reforming of methanol for hydrogen is often used in the smaller scale plant of 30~250m<sup>3</sup>/h for high purity hydrogen at 99.995-99.9999%; this process is conducted with a single reaction step at a temperature of 260-280C with low energy consumption. Thus, the onsite hydrogen production from MOH is simple with low investment and has a low energy consumption and clean operation; the cost savings from the plant capital and operation and from the hydrogen distribution expenses may make up the higher cost of MOH itself for hydrogen production.

With the carbon pollution leading to temperature hike of the earth, the development of renewable energy is receiving greater attention as the major source for energy supply. In 2019, the fossil fuel still amounts to 80.9% of world energy supply with oil (30.9%), coal (26.8%) and NG (23.2%) as the major sources; among the others 19.1%, they are from biofuel (9.4%), nuclear (5.0%), hydro-power (2.5%) with the wind and solar power being only 2.2%. [4]. Notably, the multi-carbon fuels, coal and oil still supply 57.7% of the world energy consumption; they are still the major source of energy and are consumed 26 times more than wind and solar energy even in 2019.

The effect of increasing the share of renewable energy such as biomass, hydraulic, solar and wind power in the electricity generation is only effective in areas where renewable energy is abundant or the population is relatively low, such as in the Nordic countries

of Norway, Denmark and Finland with abundant energy sources from wind, bioenergy and hydraulic energy [5]. Nuclear energy is often developed to help reducing the carbon pollution such as in France and Sweden [6]. The hydraulic, wind or solar power is highly desirable but is limited by the natural resource, not always available to every country; the nuclear energy, clean in carbon pollution is hampered by the political consideration in many countries. Thus, to reduce the carbon pollution in energy generation, besides the faster development of wind and solar power, a greater effort could be focused on the development of hydrogen as an energy source to provide the energy stability; a consistence and stable energy supply from the hydrogen energy is important when the fluctuating solar and wind power supply increases their share of energy supply in the future.

## Experimental and calculation

### General description of the hydrogen generator and the plants tests of 10Nm<sup>3</sup>/h and 20Nm<sup>3</sup>/h hydrogen generators in a powder metal plant.

The steam reforming reaction (SRR) system of Green Hydrotec Inc (GHT) is composed of both the catalytic heating and the MOH steam reforming operations in a single rectangular 6061-aluminum block reactor; as such, both heating and reforming facilities for converting MOH to hydrogen are installed in a single compact aluminum block reactor instead of two separate heating and reforming facilities. As an example, from a 10m<sup>3</sup>/h (Nm<sup>3</sup>/h) hydrogen generator, the heat is generated by the catalytic oxidation of MOH or 58wt%MOH/ water mixture with a 0.5% hBN-promoted 0.3% Pt/Al<sub>2</sub>O<sub>3</sub> oxidation catalyst (Johnson Matthey Co) [7]. The catalyst is filled inside several 1.5cmOD columns located in the central section of the reactor; the steam reforming catalyst is a regular commercial CuOZnOAl<sub>2</sub>O<sub>3</sub> catalyst (Süd-Chemie Catalysts Japan Inc.) filled in the surrounding 1.5cm OD columns section of the aluminum reactor body. More detail description and discussion on the design and fabrication are described in the previous publication [7]. The reforming temperature at 260-280°C is controlled by the flow rate of the MOH or 58%MOH-water fuel to have WHSV=1~4 in the OXD heating section; the crude hydrogen product from the reforming reaction is 74%H<sub>2</sub>, 24%CO<sub>2</sub> and 1.5-2.0%CO. The crude reforming hydrogen is then purified by a PSA purifier with automatic process control device for the production of pure hydrogen at 99.99999%; this complete set of 10Nm<sup>3</sup>/h hydrogen generator is then installed in a steel cabinet of 90cm x 100cm x 175cmH (100cm x 110cm x 200cmH for 20Nm<sup>3</sup>/h unit).

After satisfactory operation of the first set of two 10Nm<sup>3</sup>/h hydrogen generators by a powder metal company (Polite Metal Processing Co) for hydrogen processing of the metal fabrication, two more sets of 20Nm<sup>3</sup>/h hydrogen generators were added for the plant operation. The first set of two 10Nm<sup>3</sup>/h units had a quality test for one month; thereafter, the hydrogen generators have been operated 24 hours a day ever since Apr of 2020. The additional set of 20Nm<sup>3</sup>/h unit was installed later for additional plant operation in July 2020; both sets of hydrogen generators have been in continuous operation ever since.

In the first set, a mixture of 19.83kg/h of a 58% MOH/water mixture containing 11.50kg/h of MOH (359.4mol) is used as the reaction feed and heating fuel for an output of 2x10Nm<sup>3</sup>/h of hydrogen at a pressure of 0.5MPa and a purity of 99.999999% H<sub>2</sub> (CO, CO<sub>2</sub>, CH<sub>4</sub> and HC all under 1ppb by an independent process gas analyzer of Thales System Co. Ltd.). The molar yield of hydrogen production in this plant test is 87.2%. The plant was originally supplied with haul-in purchased hydrogen at \$1.14/m<sup>3</sup> before the hydrogen was generated with the on-site production at about 0.64/m<sup>3</sup> from MOH/water when methanol was purchased from the local detail vender at \$0.68/kg (while the import MOH is \$400/ton plus about 3% import duty and 7% other process cost in 2022). Thus, the plant has a saving of about 40% hydrogen cost by replacing the haul-in commercial hydrogen (\$0.65~0.85/m<sup>3</sup>H<sub>2</sub>); the saving was greater earlier when import MOH to Taiwan was at \$330 to 400/ton in the previous two years.

### Generation of 30Nm<sup>3</sup>/h hydrogen from an onsite hydrogen generator.

A 40Nm<sup>3</sup>/h MOH steam reformer installed in a 60cmD x90cmW x115cmH (0.62m<sup>3</sup>) cabinet is integrated with a PSA (pressure swing adsorber) purifier in a larger steel cabinet of 85cm x150cm x240cmH (3.06m<sup>3</sup>) to provide high purity hydrogen. From the PSA purifier 31.06Nm<sup>3</sup>/h of pure hydrogen (1.294mole/h) in 99.999999% H<sub>2</sub> purity with CO<1ppb is obtained from 38.46Nm<sup>3</sup>/h of crude

hydrogen (1.602mol/h) in 81.4% yield by the SRR of 21kg/h of methanol (0.656mol/h in 58%wt methanol water mixture) for feed and fuel corresponding to an overall yield of 75.4% reaction efficiency from MOH reforming to the pure hydrogen. The crude hydrogen from the SRR of MOH/water mixture has a composition of 74% $H_2$ , 23.5% $CO_2$  and 1.5% $CO$  which yield pure hydrogen in 80.8% by PSA purification.

The above 30Nm<sup>3</sup>/h hydrogen generator is integrated with a 30kWh fuel cell stack (Model: Ballard 9ssL, 9th generation short stack length, 130cm x186cm x195cmH) for a combined generation of heat and power by MOH and water. The fuel cell (FC) stack produces a net power generation of 30.76kWh (110.74MJ/h) from 34kWh generated by the FC stack after a power consumption of 3.24kWh by the pumping and control devices; the FC power generation was from 25.2Nm<sup>3</sup>/h of hydrogen input (254.02MJ/h) by the hydrogen generator with 18.25kg/h of MOH (363.91MJ/h) for feed and fuel as shown in Fig 1. The waste heat generates 360L/h of hot water at 50°C from 20°C by the reformer unit and 1380L/h at 45°C from 20°C by the FC unit; this corresponds to a combined waste heat recovery of 192.05MJ/h. This corresponds to a total energy output of 302.79MJ/h with a total thermal efficiency of 83.20% from MOH charge with 30.43% from the power generation and 52.77% from the hot water supply.

The additional data of hydrogen generations for the crude hydrogen and for the pure hydrogen production in the 7.5 to 30Nm<sup>3</sup>/h units are summarized in Table 1; the crude hydrogen is further purified by PSA to a purity of 99.9999-99.999999% $H_2$  with about 20% loss in the purification operation.

Pure $H_2$ , Nm <sup>3</sup> /h	Crude $H_2$ , Nm <sup>3</sup> /h	MOH Heat kg/h	MOH, SRR kg/h	MOH, waste kg/h	Total MOH kg/h	MOH, kg/kg $H_2^{Cr}$	MOH, kg/kg $H_2^{Pu}$	Energy input, MJ/h	Energy input, MJ/kg $H_2$	% Efficiency, crude $H_2$	% Efficiency, pure $H_2$
5	6.67	0.52	2.99	0.34	3.85	6.93	9.24	76.77	184.25	87.41%	65.52%
10	13.33	1.04	5.98	0.67	7.69	6.92	9.23	153.34	184.01	87.45%	65.61%
15	19.74	1.41	8.85	0.96	11.22	6.82	8.98	223.73	178.98	88.76%	67.45%
20	25.64	2.19	11.5	1.14	14.83	6.94	8.90	295.71	177.43	87.23%	68.04%
25	33.3	3.12	14.4	1.35	18.87	6.80	9.06	376.27	180.61	89.03%	66.84%
30	38.46	3.26	17.02	1.49	21.77	6.79	8.71	434.09	173.64	89.13%	69.52%
Average						6.87	9.02	259.98	179.82	88.17%	67.16%

**Table 1:**Efficiency of PSA purification in hydrogen from methanol



**Figure 1:** A 30Nm<sup>3</sup>/h hydrogen generator (R) and a 30kW fuel cell stack (L)

## Heat requirement and carbon emission in the hydrogen production

The energy requirement and the CO<sub>2</sub> emission in the hydrogen production from MOH, NG (methane) and from the electrolysis of water is calculated from the experimental examples of GHT and is presented in Table 2. As shown in Table 2, the hydrogen from MOH is not quite carbon free in its production; its energy consumption and CO<sub>2</sub> emission are both about the same as those from NG. However, NG is a gas and is often shipped under high pressure and requires additional energy input in the compression operation in more than one time; the additional operations will make the net energy consumption and CO<sub>2</sub> emission higher than those of MOH which is liquid under ambient conditions and can be shipped by normal ways without any need of extra energy input. The current electricity based mainly on fossil fuel has a carbon emission of 0.2-0.6kgCO<sub>2</sub>/kWh (or 0.057-0.45kg CO<sub>2</sub>/kWh in Europe in 2020); this high CO<sub>2</sub> emission of electricity will make the electrolytic process of water to hydrogen the most CO<sub>2</sub> polluted process for hydrogen production.

GHT has prepared onsite hydrogen generators of 30Nm<sup>3</sup>/h, 20Nm<sup>3</sup>/h, 18Nm<sup>3</sup>/h and 15Nm<sup>3</sup>/h hydrogen generators with the corresponding FC stacks for emergency power supply for the telecommunication stations and for the railroad communication station in Taiwan and many pure hydrogen units of 5-50Nm<sup>3</sup>/h reformers for various fuel cell usages and more than 160 units of 5Nm<sup>3</sup>/h of hydrogen generators for high altitude weather balloon filling in China since 2017.

	Methanol	Methane	H <sub>2</sub> O to H <sub>2</sub> by Electrolysis
Density at 25°C, 1.0 atm, kg/m <sup>3</sup>	792	0.716	0.0838
Heat capacity of fuel, MJ/kg	2.55	4.59	14.31
LHV of combustion, MJ/kg of fuel	19.94	50.01	120.97
Reaction temperature, °C	270	800	40
Experimental requirement of feed and fuel for H <sub>2</sub> production, kg/m <sup>3</sup> H <sub>2</sub>	0.676	0.291	4.5-5.0 kWh <sup>a</sup> (4.75kWh)
Experimental requirement of feed and fuel for H <sub>2</sub> production, kg/kgH <sub>2</sub>	8.11	3.49	57 <sup>a</sup>
Energy consumption for H <sub>2</sub> production, MJ/m <sup>3</sup> H <sub>2</sub>	13.48	14.54	17.10
Energy consumption for H <sub>2</sub> production, MJ/kgH <sub>2</sub>	161.76	174.48(179.77) <sup>c</sup>	205.20
Relative energy Consumption.	100%	104%(111%)	127%
CO <sub>2</sub> from feed and fuel consumption, CO <sub>2</sub> kg/kgH <sub>2</sub>	11.15 <sup>b</sup>	9.59 <sup>b</sup> (12.15) <sup>c</sup>	29.07 <sup>b</sup>
Relative emission of CO <sub>2</sub> emission.	100%	865(109%)	261%

(a), Power consumption for the electrolysis of water to hydrogen is 4.5-5.0 or average of 4.75kWh/m<sup>3</sup>H<sub>2</sub> (57 kWh/kg H<sub>2</sub>). (b), The emission efficiency of electric power in Taiwan is 0.51kgCO<sub>2</sub>/kWh in 2020. (c), In general, CO<sub>2</sub> from SRR feed and fuel consumption of NG is 3.49\*44/16=9.60 kg/kg H<sub>2</sub>. However, an additional 1.47kWh/kg NG power input from a 20MPa compression would be needed in the distribution operation; this additional power consumption of 1.47 kWh/kg NG increases a 5.29MJ/kg NG and 2.62kgCO<sub>2</sub>/kg NG in the conversion of NG to H<sub>2</sub>. The number in parentheses is the values after one single 20MPa compression operation.

**Table 2(1):** Energy consumption and CO<sub>2</sub> emission in H<sub>2</sub> production with 0.5kgCO<sub>2</sub>/kWh

## Results and Discussion

Hydrogen is a source of green energy and is free from carbon pollution in general usage; as a result, it is being supply through many hydrogen refueling stations as a fuel for vehicles to reduce air pollution of gasoline or Diesel oil in many counties. [8] It is also being actively pursued as an alternative source for energy development in many countries, such as Japan, Germany, USA, People of Republic of China (PRC) and S. Korea by introducing hydrogen powered vehicles and setting up hydrogen filling stations for filling hydrogen to vehicles.

Today hydrogen is industrially produced from the coal gasification, the steam reforming of natural gas or of methanol and the electrolysis of water. However, the coal gasification process, having heavy carbon pollution, is expected to be phased out soon

in the nearest future while the hydrogen from the water electrolysis has high energy consumption and CO<sub>2</sub> emission due to its requirement of 4.5-5.0kW/m<sup>3</sup>H<sub>2</sub>. Consequently, the electricity in most countries today is laden with high CO<sub>2</sub> emission in their power generation: 0.82-0.86 kgCO<sub>2</sub>/kW in China [8], 0.508 in Taiwan [9], 0.457 in Japan [10] and 0.385 in US [11] except those around North Sea or Baltic Sea having strong wind power for power generation such as in Britain (0.250kgCO<sub>2</sub>/kgH<sub>2</sub>) and Denmark (0.189kgCO<sub>2</sub>/kgH<sub>2</sub>) and France having high fraction of nuclear energy (0.057kgCO<sub>2</sub>/kgH<sub>2</sub>) [12].

Before CO<sub>2</sub> emission efficiency of the power generation is improved in the electrolysis of water, the steam reforming processes of NG and of MOH will be expected to play the major source of hydrogen in the next few decades due to their much lower energy consumption and low CO<sub>2</sub> emission, in addition to the lower cost, than the electrolysis of water for the hydrogen production as shown in Table 2. Thus, when wind or solar power become abundant, the use of renewable electricity for the electrolysis of water for hydrogen will become a cleaner process for the hydrogen production in future; the question is when will the renewable power be abundant enough to become the major source of hydrogen production. Today faster decrease or elimination of carbon pollution from the power generation with coal or oil should have greater urgency than the direct usage of renewable power for the electrolysis to produce hydrogen. Moreover, the demand for more electricity for the general population and economic growth in the world is also in the rise; the increased power from the renewable sources will be consumed fast. Hopefully by 2050-2060, the power supply by wind and solar energy may become abundant enough for use in the electrolysis of water to reduce its CO<sub>2</sub> emission in most countries to replace hydrogen production from the SRR of MOH or NG.

However, the use of renewable energy for energy supply may be nice and clean; its supply is not steady and is unstable even in a single day period and often fluctuates according to weather condition or seasonable variation. Thus, an additional stable power from the hydrogen energy will help leading to a more stable and consistent power supply to the publics besides its advantages in the energy saving and the low carbon emission.

### **Methanol process of Green Hydrotec Inc (GHT)**

GHT produces crude hydrogen with a compact MOH reformer followed by a PSA purification to a high purity. The reformer converts 58-60 wt% MOH/water mixture as the reaction feed and also as the heating fuel to hydrogen at 270°C with 86% yield and a composition of 74%H<sub>2</sub>, 24%CO<sub>2</sub> and 1.5%CO; the crude hydrogen is then further purified with a PSA to a high purity of 99.9999~99.999999%H<sub>2</sub> with CO, CO<sub>2</sub>, CH<sub>4</sub> and THC, each less than 1ppb. For a hydrogen supply of 30 Nm<sup>3</sup>/h, the hydrogen generator has only a volume of 3.06 m<sup>3</sup> standing on a 1.275m<sup>2</sup> of area; conceivably it is small enough to be installed in a medium sized pick-up truck for mobile supply of hydrogen to where pure hydrogen is needed. Furthermore, if a stable high temperature FC stack is available for high temperature generation of power with crude hydrogen higher than 60% concentration, then the above crude hydrogen from the reformer directly will be suitable for power generation. In such case, the reformer and its BOP (Balance of Plant: pumps, blower and tubing) without a purifier will be sufficient to supply hydrogen for power generation and the volume of hydrogen supply system can be reduced to 0.62m<sup>3</sup> only standing on an area of 0.54m<sup>2</sup>. A comparison of space saving with a 30Nm<sup>3</sup>/h high purity hydrogen generator with a 80Nm<sup>3</sup>/h crude hydrogen reformer is shown in Fig 2; even the reformer capacity is 80Nm<sup>3</sup>/h, its volume is only 20% of a 30Nm<sup>3</sup>/h pure hydrogen generator. After attaching a control panel to the reformer, the increase in the volume of a crude hydrogen generator would be limited; the volume of a crude hydrogen reformer will have only 25-30% of a pure hydrogen generator. ~~If comparison is done with two sets of equal capacity the effect of volume decrease would be even drastic.~~ Consequently, the volume of an onboard hydrogen generator of crude hydrogen with a high temperature FC stack will be small enough to provide the power for driving a vehicle or a ship. Under such innovation, hydrogen supply from the external hydrogen fueling station would not be needed any more and would lead to a huge saving in capital investment and in land for the hydrogen fueling system. [8]

A 7.5Nm<sup>3</sup>/h hydrogen production was subjected for the duration test since Feb. 20th of 2017, it has been continuously in daily operation over 43,900 h already as of this writing (June 5th, 2022). Moreover, a set of four reformers in 7.5, 10, 20 and 30Nm<sup>3</sup>/h were successfully pressure tested by Tüv Süd from ambient to 15MPa at 20°C and 250°C. These quality tests indicate a sound structure and construction with high product quality of GHT reformers or pure hydrogen generators.



**Figure 2A:** Comparison of a 30Nmh pure hydrogen generator with a 80Nmh crude hydrogen generator reformer)

### **Hydrogen production with low energy consumption and CO<sub>2</sub> emission.**

The hydrogen production from MOH by GHT is slightly lower in energy consumption and CO<sub>2</sub> emission than those of natural gas as shown in Table 2; the popular process of hydrogen from electrolysis of water, on the other hand, has much high energy consumption and CO<sub>2</sub> emission with the current emission efficiency of power generation in most countries as mentioned earlier. Nevertheless, the electrolysis of water is receiving great attention recently; this may be from an anticipation of abundant supply of the renewable power in future. Consequently, greater effort will be needed to reduce the emission efficiency of the power generation from the current level of 0.3-0.6kgCO<sub>2</sub>/kWh. The power in use today, however, is still laden with heavy carbon pollution from the use of coal and oil as the feed at 57.7%, or 84.9% including NG of the total energy generation; hydrogen from the electrolysis with this kind of power will still be high in CO<sub>2</sub> emission.

Shown in Table 2, the energy consumption and the CO<sub>2</sub> emission in the hydrogen production from MOH, NG (methane) and the electrolysis of water are calculated from the actual experimental examples of GHT. However, the energy consumption and CO<sub>2</sub> emission of NG in the actual cases are often from the repeated operation of compression or liquefaction during its distribution and are not included in the calculation; such operations are required to keep from the vaporization of NG due to heat absorption during shipment. Thus, these additional energy consumption (5.29MJ/kgH<sub>2</sub>) and CO<sub>2</sub> emission (2.62 kgCO<sub>2</sub>/kgH<sub>2</sub>) for each additional 20MPa compression would make the power consumption and CO<sub>2</sub> emission increase from 174.48MJ/kgH<sub>2</sub> and 9.59 kgCO<sub>2</sub>/kgH<sub>2</sub> to 179.77 MJ/kgH<sub>2</sub> and 12.21kgCO<sub>2</sub>/kgH<sub>2</sub>, respectively, in the above calculation in Table 2; therefore, the actual power consumption and CO<sub>2</sub> emission of NG will be more than those of methanol. This implies that hydrogen production from methanol has the lowest energy consumption and CO<sub>2</sub> emission among the three common industrial processes for the hydrogen generation.

### **Methanol is a convenient reservoir for hydrogen production and storage.**

The electrolysis of water can become a green process for H<sub>2</sub> supply only if sufficient renewable power is available perhaps in 2045-2050. Before then, the limited renewable power supply will be expected preferentially for the more urgent reduction of heavy pollution from the energy usages or power generation by coal and oil which are still amount to over 60.1% or 39.8% of total energy supply and for electricity generation, respectively [13]. To reduce the share of coal and oil fuels in the future, power from hydrogen

will be expected to play a major role of power supply and power stabilization. Hydrogen can be made from the steam reforming of methanol with much lower energy consumption and CO<sub>2</sub> emission with the simplicity in the facility and can be easily installed and operated in almost any place with stability and consistence in power supply.

Besides its low energy consumption, the generation of hydrogen from MOH can be achieved at a low temperature of 250-280°C with one single reaction step; in comparison, the production of hydrogen is carried out at 500-600°C from ammonia or at 700~900°C from NG with 3 to 4 reaction steps. Moreover, the shipping of MOH to the user can be carried out in a simple tank lorry under ambient condition whereas the shipping and storage of ammonia or natural gas requires special facility after high pressure-compression (15-20MPa) or liquefaction with higher energy consumption and CO<sub>2</sub> emission. When hydrogen is generated onsite from MOH, all the pipe connection system is preset with safety inspection at the time of installation; there is no need of valves re-connection or pipe flushing. When hydrogen is supplied from outside source with frequent making-up processes, hydrogen accident can happen by air in the connection system during such valve reconnection or fluxing of air in the piping system; thus, accident from such making up supply is avoided in an onsite production.

The conversion facility for MOH to high purity hydrogen in the GHT production is simple, compact and easy at any place any time; therefore, MOH can be treated as a hydrogen reservoir for safe and immediate generation of hydrogen from an onsite facility or from a moving vehicle or ship by an onboard hydrogen generator.

One of the drawbacks for the onsite hydrogen production from MOH is the onsite cogeneration of CO<sub>2</sub> whereas the production of hydrogen from ammonia has its CO<sub>2</sub> emission at the site of ammonia production and can be reduced or removed in the production site in advance which requires high temperature (450-650°C) and pressure (20MPa) in the ammonia synthesis. However, the CO<sub>2</sub> emission in the methanol process can be also be reduced or eliminated with an onsite absorption by alkali solution or membrane adsorption[15]; GHT has provided her own proprietary process for the CO<sub>2</sub> elimination. In other word, the difference between the ammonia process and MOH process is not the emission of CO<sub>2</sub> itself; it is the difference in the condition of CO<sub>2</sub> capture. Moreover, it is not a clear-cut or definite assessment of the two processes, the CO<sub>2</sub> emission and the energy consumption and simplicity are to be compared together as well.

### **Need of hydrogen energy to provide energy stability and consistence.**

Renewable power from wind and solar energy is clean and green; however, it varies in a day and night and fluctuates in different seasons such as summer and winter and under different weather conditions such as typhoon days, rainy day and sunshine day. As such, a quick and controllable generation of energy source is required to provide smooth and consistent energy supply to economy and daily life; the GHT process shows that MOH being low cost in distribution and stable in storage can be instantly converted to hydrogen and then electricity power via fuel cell. Thus, MOH can be quickly converted to hydrogen and electric power by fuel cell to smooth out the fluctuation of renewable power when it happens in a day or caused by the change of weather condition.

As such hydrogen energy can play a third source of energy to wind and solar energy in providing the stability to the renewable energy supply. This stabilizing role of hydrogen energy will allow the fluctuation of wind and solar energy to smooth out for daily life. The conversion of MOH to hydrogen is instant and onsite or even onboard; as a result, MOH is a practical hydrogen reservoir for the supply of hydrogen and electric power with fuel cell combination.

### **Conclusion**

Being a liquid, MOH can be distributed with low cost and ordinary facility; it can be used as an energy fuel freely to become a convenient energy source. Moreover, with the progress in the hydrogen conversion technology and the facility shown herein, the conversion of MOH to hydrogen is achieved with simple onsite conversion any time any place to solve the pity side of hydrogen in the shipping and storage; thus, liquid MOH can be treated as a hydrogen sink or reservoir for hydrogen storage for the onsite

conversion to hydrogen. Interestingly, in the future it may even become the end product of CO<sub>2</sub> recovery by the hydrogenation to methanol; this development will make hydrogen from MOH in a green arena and make MOH belong to a renewable energy. As a result, liquid MOH, besides its low cost and safety in the distribution, its low energy consumption and low CO<sub>2</sub> emission in the conversion to hydrogen will make MOH as an ideal reservoir of green hydrogen for its application in the energy development and chemical or metallurgic process in the future. Moreover, due to the easy and simple conversion of MOH to hydrogen any time any place, the hydrogen energy from MOH will play a role of stabilization to solve the fluctuation of wind or solar power. Thus, the power from wind and solar and the hydrogen from MOH will become the triple pillars of future energy supply; such a combination of energy sources from the low-cost wind and solar power may help stabilize the high fluctuating cost of MOH (US\$200~450/MT between Jan 2020 and Dec 19 2021) and result in forming a stabilizing mechanism for the energy cost. It may also provide a relief for the coal industry to shift its coal production to the methanol production from their coal gasification operation.

Hydrogen as the future energy fuel will be an idea choice as a fuel for thermal as well as for electric process; it can be used as a heating fuel in engine, boiler or heater and can be integrated with fuel cell for electricity generation. The major drawback of using hydrogen as an energy carrier from its high cost in the distribution and safety threat with high pressure storage and connection operation can thus be avoided.

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