CO_2 Emission Reduction Analysis of Bio-Hydrogen Network: An Initial Stage of Hydrogen Society

Hendrawan and Kiyoshi Dowaki

***Abstract*—This article presents a case study about regional network of bio-hydrogen supply-chain to discover the key indicators of sustainability of bio-hydrogen energy network in initial stage. The sustainability factor is focus on CO_2 emission abatement from introduction of bio-hydrogen network scenarios in comparison with the conventional system. The conventional hydrogen production method is steam methane reforming (SMR) from natural gas in Japan. The proposed hydrogen production system is a gasification process due to waste woody biomass as a feedstock and it produce in ASEAN member countries and then exporting to Japan. The feedstock is waste wood due to logging activity and production of pulp paper and furniture in the natural forest and forest plantation. The Life Cycle Inventory (LCI) analysis estimated the carbon dioxide (CO_2) emission in consideration of hydrogen form variation (liquid and gaseous phases). The results show that the high consumption of electricity in production system and the emission factor of electricity grid in each country play significant role to reduce CO_2 emission. Regional network of bio-hydrogen energy can be use for the international negotiation on climate change to drive the energy policy in national and local scale.**

***Index Terms*—Bio-hydrogen, waste woody, LCI, energy network.**

I. Introduction

According to the International Energy Agency, the world supply of primary energy (oil, natural gas, coal, nuclear sources, and renewable energies) was 12.7 billion ton of oil equivalent. Fossil energies are by far the most widely used, providing over 80% of the world supply of primary energy. Oil represents the most important share (32.4%), in comparison to coal (27.3%), natural gas (21.4%), renewable energies (12.4%), and nuclear power (5.7%) [1]. Due to this data, it indicates that the world is still facing the dependency on fossil fuel. Petroleum-based fuels became the primary source energy for transportation needs in the 20th century and continued in the beginning of the 21th century with almost all vehicles running [2].

The concentration of carbon dioxide (CO_2) in the atmosphere has unambiguously increased since the beginning of fossil fuel era in 1751 [3]-[5]. This rise in CO_2 concentration has raised concerns about possible impacts of enhanced greenhouse gas emission to the global warming problem. One of the primary contributors to this increase has been the combustion of fossil fuels.

Due to excessive consumption and dependency on fossil fuels, the world needs a transition to a new energy system that is more sustainable. So far, there are no obvious substitution options because of several of economic and technical reasons. The new alternative energy cannot replace fossil energies rapidly and massively. Although the transition of energy predicted to be long and not easy, it must be implement immediately.

Many scientist, engineers, companies, governmental agencies are convinced that hydrogen's physical and chemical advantages will make it an important synthetic fuel in the future [6]. Hydrogen is an energy carrier, and it can produce from all forms of energy and used for power generation or as a transport fuel without CO_2 emissions, mainly in association with fuel cells [7].

Until now more than 90% hydrogen production due to fossil fuel energy such as natural gas reforming and coal gasification. However, in the manufacturing process it releases CO_2 emissions. Under these circumstances, the exploration of renewable hydrogen energy paths would be necessary, that is less emission, and the LCA methodology is important to look at the environmental impact of the introduction of new path comprehensively.

The recent study about hydrogen energy utilization is focus on production and storage technology [8]-[10]. There is lack of study about regional-network hydrogen-energy system. The energy network will be able to answer resource management challenges and to see how each country will interact and contribute to the bio-hydrogen network in a long term.

This paper discusses a case study about bio-hydrogen energy network Japan-ASEAN in early stage of world's hydrogen society, where the hydrogen demand assumed will be high in Japan, and ASEAN has opportunity as an exporter of hydrogen. ASEAN member countries located in tropical area and the role of tropical forest in this area are important as carbon capture storage and the sources of timber and other forest products. The utilization of biomass to energy is less than 2% from the total potential in ASEAN region [11]. The increasing of hydrogen demand and less utilization of biomass energy in ASEAN became the motivation of this scenario policy to elaborate the possibility of bio-hydrogen network system between Japan and ASEAN in the near future.

The objectives of this study are to find the key indicators of sustainability of bio-hydrogen energy network. The sustainability index focuses on CO_2 emission that will contribute to the global warming. Based on LCA Methodology, the specific CO_2 emissions in conventional hydrogen production and the proposed bio-hydrogen network production are compared to see the CO_2 reduction benefit. Furthermore, it will assist a country in strategic negotiation meeting and drive the country to create, develop policies, and implement energy and greenhouse-gas reduction, not only

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Hendrawan is with the Tokyo University of Science, 2641 Yamazaki, Noda, Chiba, Japan (e-mail: j7412703@ ed.tus.ac.jp).

local state but also regional policy goal.

II. METHOD AND MATERIALS

A. Scope of Study

The schematic scenario shows in Fig. 1, it will compare the life cycle CO_2 emission of hydrogen production (Well-to-Tank) between conventional system in Japan and proposed scenario. The usage of hydrogen will be the same conditions for both pathways. Therefore, in the calculation, the tank-to-wheel phase was ignored. The functional unit for this evaluation is g-CO_2/MJ hydrogen fuel. The advantages of new pathway of hydrogen system evaluate by the CO_2 emission abatement that can reach by new system in comparison with the conventional one.

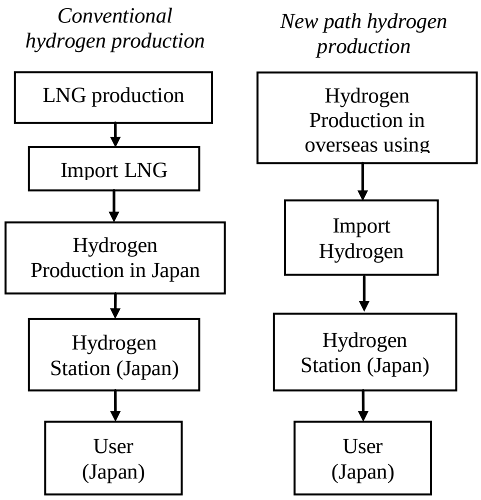

Fig. 1. The scenario of the case study.

B. LCI CO_2 Analysis Emission of Conventional Hydrogen Production

The conventional production of hydrogen fuel in Japan is mainly using steam methane reforming method from natural gas [12]. Fig. 2 shows the flow of hydrogen production in conventional system or the system boundary. Japan natural gas mainly imported from overseas such as Indonesia, Malaysia, Australia, Qatar, Brunei, Abu Dhabi, Alaska, and Oman. The study of life cycle CO_2 emission of the Japan natural gas has already done by Okamura et al, 2005[13]. That is the update version of Tamura et al. study, 2001[14].

The hydrogen production using steam methane reforming flow of process shows more detail in Fig. 3. Based on the process flow, the CO_2 heated to about 700 to 850 ^{o}C with catalyst and the preheated natural gas and steam fed into the reformer, the mixed gas is decomposed into carbon dioxide, hydrogen, and carbon monoxide. The reaction shows in Eqs. (1) and (2):

$$CH_4 + 2H_2O \longrightarrow CO_2 + 4H_2 \tag{1}$$

$$CH_4 + H_2O \longrightarrow CO + 3H_2 \tag{2}$$

The temperature reformed gas coming out from the reformer is around 700-850 ^{o}C. In the cooling process through heat exchange, the process gas decreases the temperature to around 500 ^{o}C. In the next step, CO shift converter with Fe catalyst (reaction temperature 350 to 400^{o}C) worked at a high temperature, and the gas converted into carbon dioxide and hydrogen through CO shift-converter with Cu catalyst (reaction temperature 200 to 250 ^{o}C). This CO shift reaction shows in Eq. (3):

$$CO + H_2O \longrightarrow CO_2 + H_2 \tag{3}$$

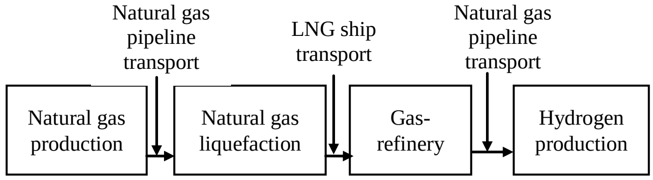

Fig. 2. The system boundary $LCCO_2$ of conventional hydrogen production.

On the performance results of the CO shift-converter, the reforming ratio is 96%, and the concentrations of H_2, CO_2, CO and CH_4 are about 78 vol.%, about 20 vol.%, about 0.5 vol.% and about 1.5 vol.%, respectively. In the hydrogen purification process, an absorbent removes carbon dioxide and/or other hydrocarbon gases. H_2, concentration reaches more than 97 vol.%. Note that the auxiliary power for compression of hydrogen is required. For producing liquid hydrogen, the reformed gas is purified to highly concentrated raw-hydrogen gas compressor then cooled by liquid nitrogen and liquefied by several stages of hydrogen turbine expanders. Also, the auxiliary power would be occupied to some extent. The SMR plant produces 418 t/day. The production use of natural gas feeds 65.6 million scf/day in the plant conditions of plant efficiency of 83.9%-HHV and net power consumption of 6 MW.

C. LCI CO_2 of Bio-Hydrogen Fuel through Gasification

The conceptual for biomass allocation shows in Fig. 3 where the biomass for energy is by product from the furniture and pulp-paper industries. According to the potential of biomass in ASEAN countries studied by Kim *et al*. 2004 [15] and Sasaki *et al*. 2009 [16], the mean annual waste wood for energy production is 563.4 million tons/year.

The waste wood is carbon neutral material but on the other hand, due to the demand of energy in process it is important to consider the inventory analysis of CO_2 emissions since cultivation process. The system boundary of the LCI CO_2 emissions for the bio-hydrogen production shows in Fig. 4. There are the following 5 main step processes; the cultivation process of trees, the pre-processing of feedstock, the production of hydrogen, the hydrogen refinery and the transportation to deliver the fuel to Japan. The plant scale is 36 t-dry feedstock/day.

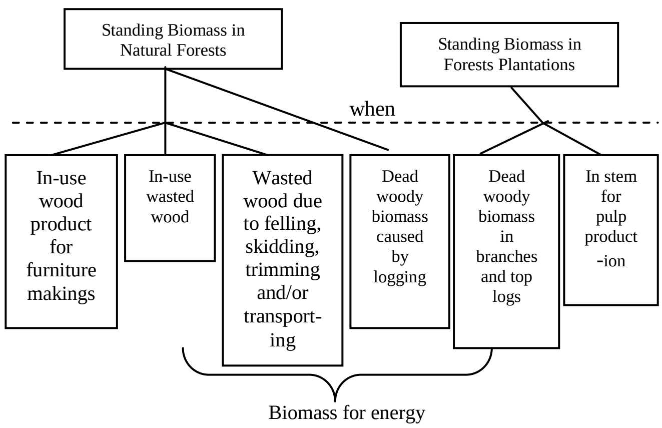

Fig. 3. Biomass allocation [16].

1) Cultivation process

The species of tree for logging is fast growing tree, *Acacia sp*. and *Eucalyptus sp*. The energy demand in the cultivation process is assumed to be the energy consumption for the pumping in irrigation process, fertilizer production, bulldozer usage and logging. The process condition and energy input factors adopted the conditions of Dowaki, 2002 [17].

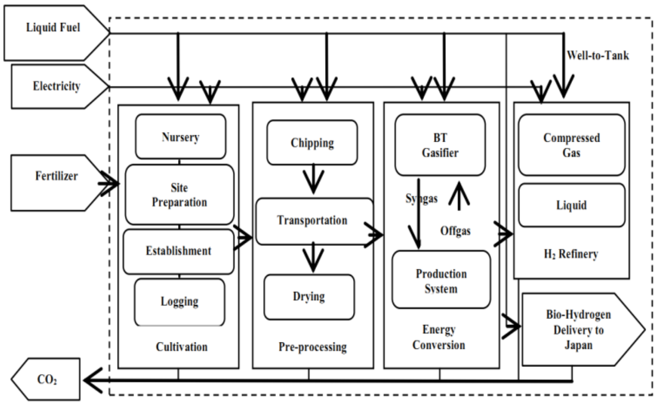

Fig. 4. The system boundary LCI CO_2 of bio-hydrogen production through gasification.

2) Pre processing

First, there is a chipping process of biomass to adjust a uniform size of the feedstock. This process requires 13.6 kWh/ton of biomass and diesel fuel 1.23 l/ton of biomass. Next, the woody chips deliver to the gasification plant and the distance between cultivation area and gasification plant assumed in the range 5-50 km. The truck capacity is 10 ton or 24.7 m^3. The moisture content of feedstock in this study is assumed to be between 20-50 wt. % and that is dried at 20 wt. % in the drying process. The energy demand is 0.195 kWh/ton water.

3) Bio-Hydrogen production and refinery

The research and development on the Blue Tower (BT) biomass gasification system in Japan, has implemented since the beginning of year 2000. The system in which the pyrolysis and reforming reactions occur under reductive atmosphere can synthesize the higher concentration of hydrogen gas efficiently (see Fig. 5). So far, we executed the studies in order to confirm the absolute proof of the chemical equilibrium reactions, and/or the demo-plant (1t/d scale) at Izumo, Japan. We also developed simulator of BT process in order to estimate the operational performance. This simulation program uses the parameters estimated by the experimental results in a room condition. Kameyama et al., 2010 [18] compared the operational result of the demo-plant to the result of the simulator, and according to this study, the simulated data were corresponding with practice data to some extent. Moreover, the bio-hydrogen plant, which is a commercial 15 t-dry/d scale constructed at Fukuoka, Japan.

The calculation of the simulator developed by Dowaki et al. 2007 [19] with several conditions as follows:

- The reaction temperature in each furnace (pyrolyzer and reformer) and steam feeding rate are fixed.
- Based on the gaseous yields in the pyrolysis and/or the reforming reactions, which analyzed by gas chromatograph, the gaseous components in each furnace were estimated due to the following two equilibrium reactions. Note that the measured gaseous components are H_2, CO, CO_2, CH_4, C_2H_4 and C_2H_6.

The gasification process after the pyrolysis reaction is shown in the following reactions Eq. (4) and Eq. (5):

$$CH_4 + H_2O \longleftrightarrow CO + 3H_2 \quad (4)$$

$$CH_4 + H_2O \longleftrightarrow CO + H_2 \quad (5)$$

The design plant of bio-hydrogen in this study is 36 t-dry/day. That is, that has the following performance: the operating time of 300 days/year, the cold gas efficiency of 59.9%-LHV, the auxiliary power of 8552 MWh/year and the annual production of hydrogen of 9.94×10^7 MJ/year MJ/year.

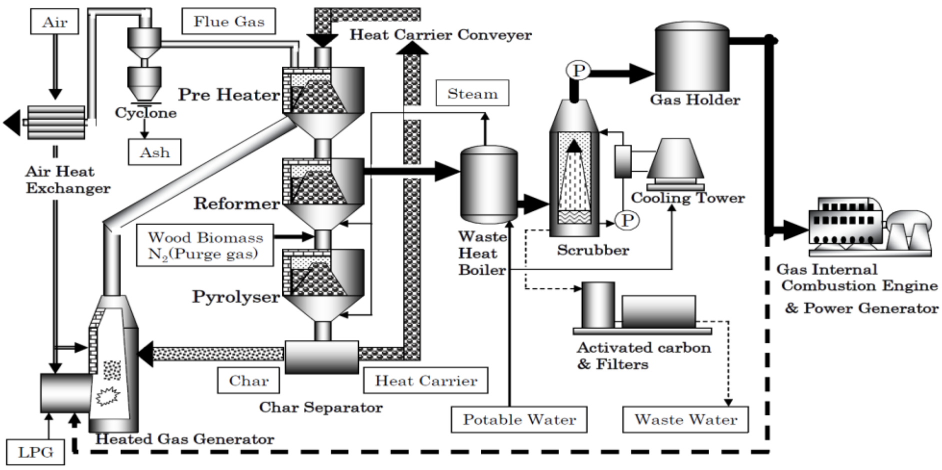

Fig. 5. Schematic design of blue tower plant [18].

4) Transportation

As the initial stage of bio-hydrogen energy network between ASEAN and Japan, we designed the bio-hydrogen energy path on basis of BT plant operation. In this scenario, the members of ASEAN will produce hydrogen fuel (hydrogen supplier) and export to Japan. However, note that each country builds a hydrogen production plant and that the waste woody biomass use as feedstock. Considering this scenario, we investigate the CO_2 emission reduction by the production of hydrogen in ASEAN country.

The shipment of the hydrogen storage tank and/or transportation distance will influence CO_2 emission of bio-hydrogen network. We assumed the distance between the origin countries as the producer of hydrogen (ASEAN member countries) and the destination is Japan as consumer of hydrogen (see Table 1). Dowaki et al., 2012 [20] studied the fuel (heavy oil) consumption of the vessel and the emission factor for transporting hydrogen with several phase. The fuel consumption of tanker ship for compressed gas hydrogen is 318.5 l/year/km and hydrogen liquid phase is 32.18 l/year/km. The tanker ship uses heavy oil with the emission factor of 2322 g-CO_2/l.

TABLE I: THE VESSEL TRANSPORT DISTANCE TO JAPAN

Port Country Origin	Distance (km)
Brunei	4757
Cambodia	5029
Indonesia (Kalimantan & Papua)	10849
Lao PDR	4781
Malaysia	6163
Myanmar	7909
Philippines	3529
Singapore	5783
Thailand	5813
Vietnam	4781

III. RESULT AND DISCUSSION

The total CO_2 emission of conventional hydrogen production in Japan is 63.26 g-CO_2/MJ Fuel. Fig. 6 shows the percentage of emissions for the whole life cycle in conventional hydrogen production system. From the results, we can see that the highest contributor of CO_2 emission is steam methane reforming process. It would be 80% of CO_2 emission or more. This is due to the fuel combustion in SMR process that contributes around 78.09% against the total whole life cycle. On the other hand, the natural gas production and transportation would be less than 20% against the total life cycle emission.

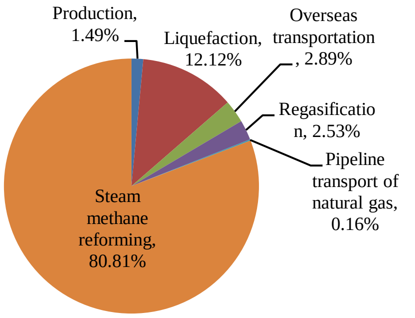

Fig. 6. The CO_2 emission of conventional hydrogen production.

Fig. 7 and Fig. 8 represent the CO_2 emissions of bio-hydrogen production in ASEAN region on both liquid and compressed gas phase. Three cases are shown in the graph, based on the uncertainties of moisture content of the biomass (minimum: 20%, average, maximum: 50%) and the land transportation distance from forest area to the BT plant (minimum: 5 km, average, maximum: 50 km). From these figures, we can see that the bio-hydrogen network ASEAN-Japan will give CO_2 emission reduction, if Japan imports bio-hydrogen as a compressed gas from Lao PDR, Myanmar, and Vietnam (minimum condition).

The highest contributor of CO_2 emission is the gasification and transportation processes (see Fig. 9 and Fig.10). The CO_2 emission in gasification process is due to the high consumption of auxiliary power in the process. The emission factors of electricity grid in Lao PDR and Myanmar are the lowest among ASEAN member countries. This difference is because of the variation of energy mixing policy for production of electricity in each country. From this viewpoint, the countermeasure for decreasing conventional electricity is one of the main indicators for reducing CO_2 emission of hydrogen fuel.

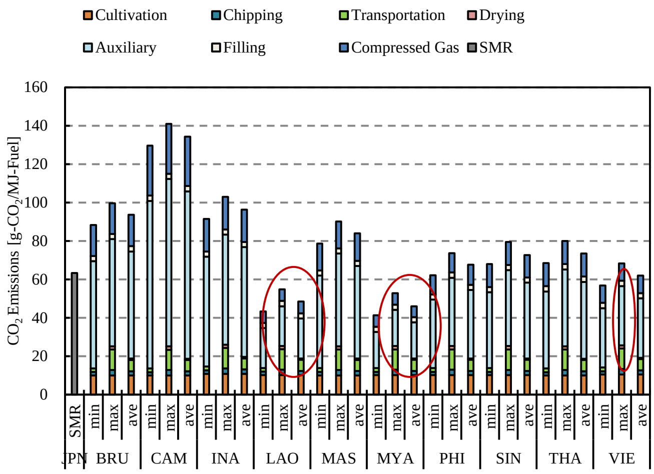

Fig. 7. CO_2 emission of bio-hydrogen production (compressed gas storage).

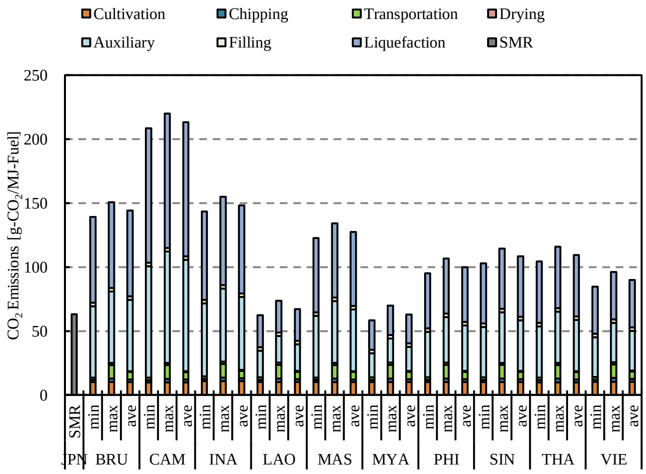

Fig. 8. CO_2 emission of bio-hydrogen production (liquid storage).

Indonesia, Philippines, Thailand, and Malaysia have great potential of waste wood resources for hydrogen production due to the large forest area. On the other hand, if the production is executed in home country, it will not give any benefit for the climate change protection. Another opportunity for these countries is to deliver the waste biomass resource to Lao PDR, Myanmar, Vietnam, and Japan. Brunei Darussalam and Singapore have a less potential of waste wood but there are possibility to build the gasification plant in this country if they can reduce the emission factor of electricity grid.

In the term of technological improvement of gasification process, it is also important to have more efficient energy consumption in the whole process. For the R&D of this technology, somewhat improvement of not only technical problem but also all aspects including supply chain would be required. From this discussion, we can conclude that there is no single solution to build the bio-hydrogen energy network, and that the solution would be led through policy options on the hydrogen society in each country in the near future. Therefore, in the next step, it is important to see the effects of the dynamic policy option by simulating the several key policy options in this study. The optimization model to see the ideal condition or the least cost option in the network system now is under developing.

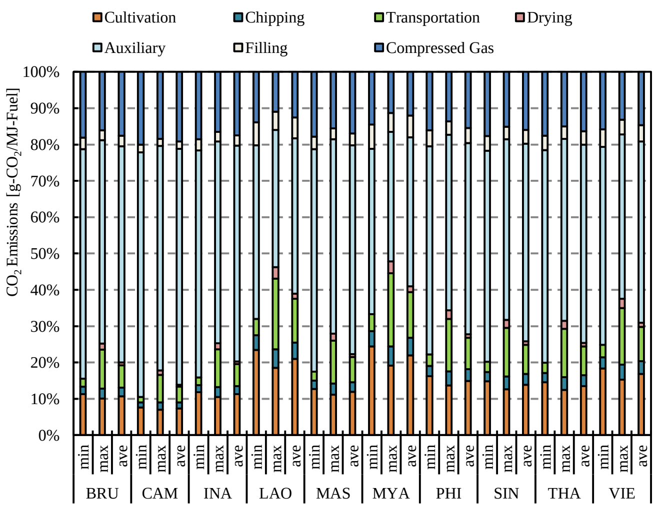

Fig. 9. The fraction of CO_2 emission in bio-hydrogen production (compressed gas storage).

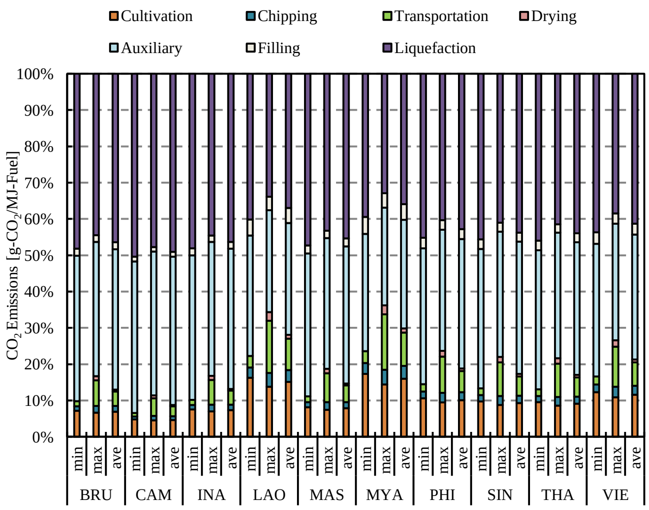

Fig. 10. The fraction of CO_2 emission in bio-hydrogen production (liquid storage).

This result shows contradictive with another works in Spain [21], where the hydrogen from woody biomass can reduce CO_2 emission in comparison to the conventional natural gas reforming hydrogen. The difference is due the different assumptions and scope in the life cycle. The previous work did not consider exporting the fuel to another country. From this point, is it also important to see the possibility to use the hydrogen in local area or to elaborate the hydrogen market possibility in ASEAN in the future.

IV. Conclusion

Through this study, we can conclude that although the waste woody biomass is carbon neutral resource and has a great potential to produce hydrogen. However, considering the hydrogen production of biomass origin, the auxiliary power and the transportation energy consumption due to fossil fuel use have to be included in our estimation.

As the results, in ASEAN region, countries who have plenty waste woody biomass cannot give a benefit to reduce CO_2 emissions based on the described scenario. The CO_2 emission of conventional electricity grid in each country is the most important role for CO_2 abatement benefit. For the future research, it would be significant to investigate the other scenario policies and the effect of dynamic policy such as supply-chain waste biomass, emission factor projection of electricity grid to the development of hydrogen fuel.

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Hendrawan was born in Sumedang, Indonesia. He got his bachelor degree in environmental engineering from Bandung Institute of Technology-Indonesia in 2005 and he received double master degree in system engineering from Tokyo University of Science-Japan and science in management from Bandung Institute of Technology-Indonesia in 2010. Now he is a doctor candidate of system engineering in Tokyo University of Science.

Kiyoshi Dowaki was born in Tokyo, Japan. He received his doctor degree of engineering in geo-system engineering from University of Tokyo, Japan in 1997. He is currently a professor at Tokyo University of Science and the head of Department of Industrial Administration.