Techno-Enviro-Economic Study of Hydrogenated Vegetable Oil Production from Crude Palm Oil and Renewable Hydrogen

A H Vivadinarto¹, W W Purwantö¹∗
Sustainable Energy Systems and Policy Research Cluster, Department of Chemical Engineering, Faculty of Engineering, Universitas Indonesia, Depok, 16424, Indonesia

*widodo@che.ui.ac.id

Abstract. From the perspective of technical, environment, and economics, hydrogenated vegetable oil (HVO) production with renewable hydrogen from biomass gasification (BG), geothermal electrolysis (GEO-E), and solar photovoltaic electrolysis (PV-E) is compared to steam methane reforming (SMR). The purpose of this study is to evaluate the energy efficiency, greenhouse gases emission factor, and production cost of HVO from various hydrogen production technologies. Production technologies are simulated using Aspen Plus®. HVO is produced by hydrotreating and hydroisomerization reactions. The processes produce three main products: HVO, green naphtha, and bio-jet fuel. The feedstock used to produce hydrogen from BG is empty fruit bunch (EFB). Renewable electricity produced by geothermal combination of flash system and organic Rankine cycle (ORC) and solar photovoltaic (PV) with battery. Technical analysis is done by calculating the energy efficiency of overall system. Production cost of HVO is calculated by levelized cost of energy (LCOE). Life cycle analysis (LCA) is carried out to calculate CO₂-eq intensity. The result shows that HVO production with SMR has the highest energy efficiency, 55.67%, which then followed by BG, 31.47%, PV-E, 9.34%, and GEO-E, 7.89%. The order of LCOE obtained from lowest to highest is HVO production from hydrogen produced by SMR (15.78/GJ-HVO), BG ($16.37/GJ-HVO), GEO ($22.83/GJ-HVO), and PV ($27.29/GJ-HVO). However, for CO₂-eq intensity, the order is HVO productions with the hydrogen produced by GEO-E, PV-E, SMR, and BG are 1.63 kgCO₂-eq/kg HVO, 1.86 kgCO₂-eq/kg HVO, 5.57 kgCO₂-eq/kg HVO, and 16.52 kgCO₂-eq/kg HVO, respectively.

1. Introduction
Through the biofuel blending mandate (Regulation of MEMR No. 12/2015), the government of Indonesia has decided to shift transportation fuel into an environmentally friendlier option. This mandate rules the government’s target of the biodiesel uses for non-public service obligation (PSO) transportation by 2020 and 2025 to be 30% from total need [1]. It should be noted that 30% is also the highest blending target possible to be reached by the fatty acid methyl ester (FAME), due to the nature of the fuel in an unmodified diesel engine complying to the blended fuel standard ASTM D7467 [2]. While government has expressed its plan to blend 50% of biodiesel, such plan will not be plausible if FAME is still being used, unless a substitute for FAME is proposed. One of the potential alternatives is hydrogenated vegetable oil from crude palm oil (CPO).

Commercial production of HVO has been demonstrated from edible vegetable oils with claims of usage in unmodified diesel engine. Neste, one of the producer of HVO, has their production plant widely spread in Europe and Asia [3], [4]. Eni with Honeywell-UOP have also converted their conventional refineries into bio-refineries to produce HVO [5]. These production technology of HVO through
hydrogenation reactions followed by isomerization [5], [6]. The former involves treating triglyceride with hydrogen to produce long chain paraffin, while the latter restructure paraffin to improve its cold properties.

Technical and economic analysis had also been discussed widely. Technical analysis simulates the production of HVO mainly through a series of reaction of hydrogenation, decarboxylation, and decarbonylation to attain high levels of n-C_{15} to n-C_{18} [7], [8]. Although most process simulation studies only simulated the hydrogenation process and hydrogenation followed by isomerization corresponding to available commercial production with co-products of green naphtha and bio-jet fuel [9], [10], [11]. A similar study analysed the sensitivity of HVO production from rubber seed oil to evaluate the economics and it showed that the production cost is driven by feedstock and hydrogen prices [11]. A techno-economic of HVO production using crude palm oil (CPO) is also performed by Martinez-Hernandez [9] where it revealed that production cost for HVO is a more viable investment than for bio-jet fuel due to current product price trend. It also explained that the most affecting cost for HVO production is feedstock price, followed by hydrogen price and capital cost [9]. These previous studies have shown sensitivity of pure hydrogen price, but none of them has ever counted the cost of hydrogen from several supply paths.

Based on a report published by IEA [12], the supply of hydrogen is one of the challenges to produce HVO. HVO production must have an economically and environmentally viable hydrogen supply. An ERIA study [13] reported that various hydrogen production technologies have differ in cost trends and CO_2 footprints, making these two factors as determining acceptable decision for HVO production path. Neither any of the previous studies has considered these two factors. Therefore, this work aims to assess the technical, economical, and environmental aspects of HVO production with different hydrogen supply sources. These hydrogen production technologies include steam methane reforming (SMR), biomass gasification (BG), solar photovoltaic (PV) power with electrolysis (PV-E), and geothermal power with electrolysis (GEO-E).

2. Methods
The technical, economic, and environmental perspective is carried out in this study. Overall system efficiency is performed to evaluate the technical performance. Life cycle analysis (LCA) is measured to evaluate CO_2-eq intensity. Finally, an economic analysis is done by levelized cost of production for each configuration.

2.1. Process Simulation
Process simulation is conducted using Aspen Plus® v.11 with a flow diagram as shown on Figure 1. The capacity of HVO production is set to one million tons per year corresponding to the typical commercial HVO production. An assumption of hydrogen being directly fed to the HVO production is taken.

![Figure 1. Process flowsheet of hydrogen and HVO production.](image-url)
2.1.1. **Hydrogen Production.** Reactions of SMR are simulated by the reactor blocks in Aspen Plus. The first reactor is to simulate the “pre-reforming” section which is consequent to the reforming reactor. This reforming reactor is modelled using the tool block RPLUG, with the condition operation and reaction kinetics adopted from [14]. In order to maximize the yields of hydrogen production, water gas shift reactor is incorporated after the reforming reactor [15]. Several studies have stated an efficient performance to purify the hydrogen from reforming reactor using pressure swing adsorption [16], [17]. Thus, a pressure swing adsorption is modelled to purify the hydrogen to 99% using the SEPARATOR block with condition operation adopted from the experiment study of Ribeiro, et. al. [17].

BG system is simulated the gasifier followed by water gas shift and pressure swing adsorption. The biomass used is palm oil empty fruit bunches (EFB). Modelling the EFB in the simulator is done by inputting the proximate and ultimate analysis adopted from [18]. A series of reaction occurs in the reactors modelled using the kinetics that is adopted from [19]–[22] with operation condition of the gasifier adopted from [18], while the steam to biomass ratio is set to be 2, complying to the range set in [23].

Electrolysis used for the production of hydrogen is alkaline electrolysis (AEL) with solar energy and geothermal energy as its energy source. Due to the unavailability to model AEL reaction in Aspen Plus, CALCULATOR block is used alongside RSTOIC. CALCULATOR block has a built-in Fortran which enables to model the reaction using the equation adopted from [24]. Physical characteristics of AEL module, such as active area and current density are based on operating data taken from [25].

PV array is located in South Sumatra with daily GHI of 5.21 kWh/m² and equipped with electricity storage because electricity supply must be continuous to support the production of HVO for intermittent electricity from Solar PV [26]. The efficiency of the Solar PV is 17.54% based on the World Bank Report [26], while the efficiency of the Li-ion battery is 90% [27]. PV array is designed using the equation 1 with $A_{PV}$ being area of PV array needed (m²), $L_{el}$ being the electricity needed, $H_{avg}$ being the GHI (kWh/m²). Battery size is designed using the equation 2 where $B_{sc}$ is battery capacity (MWh), N is hours of no sun (h), and DOD is Depth of Discharge (%).

\[
A_{PV} = \frac{L_{el}}{H_{avg} \times \eta_{PV} \times \eta_{B}} \tag{1}
\]

\[
B_{sc} = \frac{N \times L_{el}}{\eta_{B} \times DOD} \tag{2}
\]

Similar to PV array, geothermal power plant is set to be at South Sumatra. A combination of Organic Rankine Cycle (ORC) and flash type geothermal power plant is assumed to be used and the efficiency of power plant is 13.37% [28].

2.1.2. **HVO Production.** The production process is assumed to have a capacity factor of 91%. Products resulted from the plant are HVO, green naphtha, and bio-jet fuel. The simulation is ensured to produce those three products complying to the standard and commercial product specification, such as EN 15940:2016, EN 590:2013, ASTM D975:15b, and the commercially available products as seen on [29]–[31]. CPO, as the feedstock, is modelled as refined, bleached, deodorized, palm oil (RBDPO), where the composition of this feedstock is adapted from [10], due to higher HVO yield achieved by reacting RBDPO with hydrogen instead of untreated CPO according to [32]. The processes of HVO production consists of three section: (1) hydrotreating, (2) hydroisomerization, and (3) product separation.

The reactors used in the processes are for hydrotreating reaction and hydroisomerization reaction. Hydrotreating reactor is modelled using the tool REQUIL in Aspen Plus where the stoichiometric reaction adopted from Manco et al[10]. Hydroisomerization reactor is modelled using the RYIELD tool and based on the experiment in [33]. Purifying the paraffin from unreacted hydrogen and water is done by using two phase separators.
Product separation uses two distillation columns and are modelled using the RADFRAC tool. The top product of the first distillation column separates C3 to C9, which consequently must be passed into a decanter to separate the C3 from the product. C3 produced is used as fuel for the plant, while the rest C4 – C9 is sold as green naphtha. Bottom product of the first distillation column passed into the second distillation column to produce bio-jet fuel (C10-C14) and HVO (C15-C18).

2.2. System Efficiency
Overall system efficiency for SMR, BG, and HVO production are defined by the equation 3.

\[ \eta_j = \frac{\sum m_i HHV_i}{\sum m_k HHV_k} \] (3)

Where \( \eta_j \) is energy efficiency for each technology, \( m \) is mass flow (kg/h), \( HHV \) is Heating Value (MJ/kg), \( i \) is the type of input flow, \( k \) is the type of output flow.

Equation 4 is used to calculate the system efficiency in electrolysis is as followed.

\[ \eta_{electrolysis} = \frac{m_{H_2} HHV_{H_2}}{P} \] (4)

Where \( \eta_{electrolysis} \) is system efficiency for electrolysis, \( m_{H_2} \) is mass flow of hydrogen (kg/s), \( P \) is power needed for electrolysis (W), \( HHV_{H_2} \) is hydrogen heating value (J/kg).

2.3. Cost Evaluation
Cost evaluation is done using levelised cost of production of hydrogen and biofuels. The methodology used is levelised cost of energy (LCOE) which considers capital expenditures (CAPEX), fixed operation and maintenance expenditures (OPEX), and feedstock cost of expenditure (FS). The equation used for this methodology is expressed in Equation 5 with \( C \) being the CAPEX (\$), \( O \) being the OPEX (\$/year), \( F \) being the FS ($/unit feedstock), \( CRF \) being the cost recovery factor as a function of lifetime and discount factor, where the plant lifetime is assumed to be 30 year and the discount factor is 10%, \( CF \) being the capacity factor (%), and \( q \) being the production capacity (ton/year). CAPEX is estimated based on Table 1 and using the sixth-tenth rule for adjustment of the plant scale.

\[ sLCOE_{it} = \left( \frac{[C_{it} CRF_{it}] + O_{fixed, it} + F_{it}}{8760 \times CF_{it} \times q_{it}} \right) \] (5)

Table 1. CAPEX and OPEX data.

| Technology               | CAPEX | OPEX (USD/y) | Ref.  |
|--------------------------|-------|--------------|-------|
| Solar PV                 | 1,158.00 USD/kW | 1% | [34] |
| Battery                  | 298.00 USD/MWh | 2.50% | [35] |
| Geothermal Power Plant   | 5.67 M USD/MW | 2% | [36] |
| Electrolyser             | 840.00 USD/kW | 2% | [37] |
| SMR                      | 1.02 M USD/ton/day | 5% | [38] |
| BG                       | 360 × (\frac{capacity}{150})^{0.75} M USD/ton/day | 5% | [39] |
| HVO Plant                | 1,200 M USD/MT/year | 6% | [40] |
Table 2. Feedstock cost of expenditure.

| Feed       | Price         |
|------------|---------------|
| CPO        | $0.60 per kg CPO |
| EFB        | $0.045 per kg EFB |
| Natural Gas| $6 per MMBtu   |

The CAPEX projection is predicted to evaluate cost reduction in the future for HVO production with renewable hydrogen, especially from GEO-E and PV-E with high learning rate. Learning rate of PV, electrolyser, and battery are 37%, 55.8%, 18%, respectively [41], [42], [43].

2.4. Life Cycle Analysis

CO₂ intensity is calculated CO₂ footprint every configuration. The methodology used is life cycle analysis (LCA) of cradle-to-gate with the system boundary covering the production of hydrogen to the end-product of HVO (Figure 2). The functional unit in this paper is set as kg-HVO.

Sources of life cycle inventories for this study are based on process simulations for hydrogen productions and HVO productions, and the others (CPO and EFB) are taken from [43], natural gas [44], PV electricity [42], and geothermal power plant [28].

3. Results and Discussion

3.1. System Efficiency

The comparison of energy efficiency can be represented by the Sankey diagram (Figure 3). All HVO based renewable hydrogen technologies have lower energy efficiency than compared to SMR. The efficiency of SMR-HVO, BG-HVO, PV-E – HVO, and GEO-E – HVO are 55.76%, 31.47%, 9.34%, and 7.89%, respectively.

It is noted that renewable based electricity productions have poor efficiencies (7.89% and 9.34%) compared to its non-renewable competitor, SMR – HVO (55.76%). The fall of efficiencies are rooted from electricity productions as additional process which required more energy consumptions. For continuous production of HVO, PV-E – HVO requires Solar PV to generate electricity and the battery to handle intermittently production of electricity, while GEO-E – HVO requires electricity generation through geothermal power plant. Although PV-E – HVO requires battery and GEO-E – HVO does not, GEO-E – HVO still has worse efficiency due to low efficiency of electricity generation (13.37%), while electrical generation using solar PV alone has better efficiency of 15.82% and a good efficiency of battery (90%).

BG – HVO efficiency falls behind SMR – HVO due to higher loss of energy during hydrogen production (Figure 3b and 3d). Higher loss of energy happens due to CO₂ emission. BG – HVO losses
3017.6 MWh due to CO₂ emission in hydrogen production, a significantly higher number compared to SMR – HVO (880.6 MWh). The wide differences were due to the C/H ratio in the feedstock. SMR uses natural gas as feedstock, which has lower C/H ratio compared to EFB, the feedstock of BG.

Figure 3. Energy flow analysis of (a) GEO-E - HVO; (b) BG - HVO; (c) PV-E - HVO; (d) SMR – HVO.

3.2. CO₂-eq Intensity
The CO₂-eq intensity for all systems without weighting are shown at Figure 7. SMR – HVO and BG – HVO have higher CO₂-eq emission than HVO produced from hydrogen-based renewable electricity. SMR-HVO presents 5.57 kg CO₂-eq/kg HVO, BG – HVO produces 16.52 kg CO₂-eq/kg HVO, while GEO-E-HVO and PV-E-HVO are 1.63 kg CO2eq/kg HVO and 1.86 kg CO2eq/kg HVO, respectively. The higher CO₂-e emissions mainly due to the hydrogen production for BG and SMR – HVO. BG uses empty fruit bunch (EFB) as feedstock with higher C/H ratio than SMR. GEO-E – HVO has lowest emission due to highest electricity generation efficiency with 0.02 kg CO₂-e/kWh [28] compare to PV electricity of .04 kg CO₂-e/kWh [44].

Figure 4. LCA of HVO production.

Although EFB has highest CO₂-eq emission, the biomass is carbon neutral by considering the CO₂ absorption during photosynthesis. Khoon, et. al. (2011) calculated the net fixation of CO₂ from palm oil plantation is 25.7 kg-CO₂/ha/hr [45]. Additionally, by using carbon capture, bioenergy carbon capture
and storage (BECCS) that is a reliable path for negative emissions as shown in Figure 5. HVO production with BECCS produces -44.4 kg CO₂-e/kg of all products.

3.3. Economic Performance

CAPEX breakdown of each configuration is presented in Table 3. Hydrogen production-related CAPEX dominates share of HVO investment. This is affected by the developing technologies for all renewable hydrogen technologies, whereas SMR, as non-renewable hydrogen technology, has already in its lowest cost.

Table 3. CAPEX value and share.

| Technology       | H₂ Prod. Plant | HVO Prod. Plant | Electricity Generator |
|------------------|----------------|-----------------|-----------------------|
|                  | Total Inv. a Share | Total Inv. a Share | Total Inv. a Share |
| SMR – HVO        | 139.3           47%           | 123.2           53%           | -                  |
| BG – HVO         | 234.4           66%           | 123.2           34%           | -                  |
| GEO-E – HVO      | 279.4           48%           | 123.2           21%           | 180.3             31% |
| PV-E – HVO       | 285.1           12%           | 123.2           5%            | 1973.9            83% |

aTotal Inv. (total investment) is in M USD

Figure 7 revealed that SMR – HVO configuration is the cheapest option driven by cost of hydrogen productions. HVO production from renewable hydrogen with the lowest production cost is BG-HVO. While hydrogen productions via electrolysis give high production cost around $44.48/GJ and $53.16/GJ of total products for GEO-E – HVO and PV-E – HVO, respectively.

The levelised cost of each product is also estimated based on joint cost (Figure 8). For every technological configuration, HVO production cost based on PV electrolysis has the highest cost.
Based on higher costs of renewable electricity, battery and electrolyser, the projection of HVO production cost is carried out to evaluate when these new technologies can compete to conventional one. PV-E – HVO will surpass SMR – HVO in 2050, while GEO-E – HVO will surpass SMR-HVO in 2070. PV-E – HVO can surpass SMR – HVO faster than GEO-E – HVO due to greater learning rate.

4. Conclusion
According to the study, the best overall energy efficiency is achieved by SMR – HVO. SMR – HVO has the highest efficiency of 55.67%, while the renewable options’ efficiencies are 31.47%, 9.34%, 7.89%, for BG – HVO, PV-E – HVO, and GEO-E – HVO, respectively. Configuration with the lowest to highest CO2 emission are GEO-E – HVO (1.63 kgCO2-e/kg HVO), PV-E – HVO (1.86 kgCO2-e/kg HVO), SMR – HVO (5.57 kgCO2-e/kg HVO), BG – HVO (16.52 kgCO2-e/kg HVO). However, if BECCS is used, BG – HVO can have a negative emission with -22.79 kgCO2-eq/kg HVO. The lowest to highest LCOE are SMR – HVO ($0.59/l-HVO), BG – HVO (0.61/l-HVO), GEO-E – HVO ($0.88/l-HVO), and PV-e – HVO ($0.95/l-HVO). A projection is carried out and concluded that PV-E – HVO will be the first to surpass SMR – HVO in 2050.

Acknowledgment
The study is funded by Hibah Publikasi Terindeks Internasional (PUTI) Prosiding Universitas Indonesia, Contract Number: NKB-1105/UN2.RST/HKP.05.00/2020.

References
[1] Kementrian Energi dan Sumber Daya Alam 2014 Regulation of MEMR No. 12 Year 2015 Kementrian Energi dan Sumber Daya Alam
[2] Ali O M , Mamat R, Abdullah N R, and Abdullah A A 2015 Analysis of blended fuel properties and engine performance with palm biodiesel-diesel blended fuel Renew. Energy 86 59–67
[3] Neste Oil, “Neste Oil starts up its new renewable diesel plant in Singapore,” 2010. https://www.neste.com/neste-oil-starts-its-new-renewable-diesel-plant-singapore (accessed Sep. 24, 2020).
[4] “News: Neste Oil to build a NExBTL renewable diesel plant in Singapore,” Oil Gas European Magazine, vol. 34, no. 1. p. 50, 2008, Accessed: Sep. 24, 2020. [Online]. Available: https://www.neste.com/neste-oil-build-nexbtl-renewable-diesel-plant-rotterdam.
[5] Eni, “EcofiningTM,” Eni, 2019. https://www.eni.com/en-IT/operations/biofuels-ecofining.html (accessed Sep. 24, 2020).
[6] Neste, “NExBTL technology,” 2019. https://www.neste.com/about-neste/innovation/nexbtl-technology (accessed Sep. 24, 2020).
[7] Kittisupakorn P, Sae-ueng S, and Suwattikhul A 2016 Optimization of Energy Consumption in a Hydrotreating Process for Green Diesel Production from Palm Oil Comput. Aided Chem. Eng. 38 751–756
[8] Kiatkittipong W, Phimsen S, Kiatkittipong K, Wongsakulphasatch S, Laosiripojana N, and Assabumrungrat S 2013 Diesel-like hydrocarbon production from hydroprocessing of relevant refining palm oil Fuel Process. Technol. 116 16–26
[9] Martinez-Hernandez E, Ramirez-Verduzco L F, Amezcu-Allieri M A, and Aburto J 2019 Process simulation and techno-economic analysis of bio-jet fuel and green diesel production — Minimum selling prices Chem. Eng. Res. Des. 146 60–70
[10] Vélez Manco J F 2014 Conceptual design of a palm oil hydrotreatment reactor for commercial diesel production 122
[11] Cheah H K, Yusup S, Gurdeep Singh H K, Uemura Y, and Lam H L 2017 Process simulation and techno-economic analysis of renewable diesel production via catalytic decarboxylation of rubber seed oil – A case study in Malaysia J. Environ. Manage. 203 950–961
[12] Karatzos S, Mcmillan J, and Saddler J 2014 IEA Bioenergy Task 39 - The potential and challenges of “drop in” biofuels, July
[13] ERIA 2019 The Potential and Costs of Hydrogen Supply Demand and Supply Potential of Hydrogen Energy in East Asia, ERIA Research Project Report FY 2018 01140–183
[14] Xu J and Froment G F 1989 Methane steam reforming, methanation and water-gas shift: I. Intrinsic kinetics AIChE J. 35 (1) 88–96
[15] Muritala I K, Guban D, Roeb M, and Sattler C 2019 High temperature production of hydrogen: Assessment of non-renewable resources technologies and emerging trends Int. J. Hydrogen Energy
[16] Nikolaides P and Poullikkas A 2017 A comparative overview of hydrogen production processes Renew. Sustain. Energy Rev. 67 597–611
[17] Ribeiro A M, Grande C A, Lopes F V, Loureiro J M, and Rodrigues A E 2012 Four Beds Pressure Swing Adsorption for Hydrogen Purification: Case of Humid Feed and Activated Carbon Beds AIChE J. 59 (4) 215–228
[18] Mohammed M A A, Salmiaton A, Wan Azlina W A K G, and Mohamad Amran M S 2012 Gasification of oil palm empty fruit bunches: A characterization and kinetic study Bioresour. Technol. 110 628–636
[19] Hejazi B, Grace J R, Bi X, and Mahecha-Botero A 2017 Kinetic Model of Steam Gasification of Biomass in a Bubbling Fluidized Bed Reactor Energy and Fuels 31 (2) 1702–1711
[20] Abbas S Z, Dupont V, and Mahmud T 2017 Kinetics study and modelling of steam methane reforming process over a NiO/Al2O3 catalyst in an adiabatic packed bed reactor Int. J. Hydrogen Energy 42 (5) 2889–2903
[21] Yu J and Smith J D 2018 Validation and application of a kinetic model for biomass gasification simulation and optimization in updraft gasifiers Chem. Eng. Process. - Process Intensif. 125 February 214–226
[22] Olksbye U, Wurzel T, and Mleczko L 1997 Kinetic and Reaction Engineering Studies of Dry Reforming of Methane over a Ni/La/Al2O3 Catalyst Ind. Eng. Chem. Res. 36 (12) 5180–5188
[23] Inayat A, Ahmad M M, Mualib M I A, and Yusup S 2012 Process modeling for parametric study on oil palm empty fruit bunch steam gasification for hydrogen production Fuel Process. Technol. 93 (1) 26–34
[24] Sánchez M, Amores E, Abad D, Rodríguez L, and Clemente-Jul C 2020 Aspen Plus model of an alkaline electrolysis system for hydrogen production Int. J. Hydrogen Energy 45 (7) 3916–3929
[25] Rath M, Mayyas A, and Mann M 2017 Manufacturing Competitiveness Analysis for PEM and Alkaline Water Electrolysis Systems Fuel Cell Seminar and Energy Exposition 5–11
[26] World Bank Group 2017 Solar Resource and Photovoltaic Potential of Indonesia May 86, [Online]. Available:
[27] Tesla “Powerwall Datasheet.” https://www.tesla.com/sites/default/files/pdfs/powerwall/Powerwall_2_AC_Datasheet_en_northamerica.pdf (accessed Sep. 27, 2020).

[28] Wang Y, Du Y, Wang J, Zhao J, Deng S, and Yin H 2020 Comparative life cycle assessment of geothermal power generation systems in China Resour. Conserv. Recycl. 155 November 2019

[29] Kalnes T N, Marker T, Shonnard D R, and Koers K P 2008 Green diesel production by hydrefining renewable feedstocks

[30] Neste Corporation 2015 Neste Renewable Diesel Handbook

[31] P S & Global P 2017 Methodology and Specifications Guide Asia Pacific & Middle East Refined Oil Products

[32] Kiatkittipong W, Phimsen S, Kiatkittipong K, Wongsakulphasatch S, Laosiripojana N, and Assabumrungrat S 2013 Diesel-like hydrocarbon production from hydroprocessing of relevant refining palm oil Fuel Process. Technol. 116 16–26

[33] Hensawad T, Srimingkwanchai C, Butnark S, Resasco D E, and Jongpatiwut S 2018 Effect of Metal-Acid Balance on Hydrefined Renewable Jet Fuel Synthesis from Hydcracking and Hydroisomerization of Biohydrogenated Diesel over Pt-Supported Catalysts Ind. Eng. Chem. Res. 57 (5) 1429–1440

[34] International Renewable Energy Agency (IRENA) 2019 Renewable Power Generation Costs in 2018

[35] IRENA 2019 Utility-Scale Batteries

[36] Sarulla Operations Ltd 2020 No Title https://sarullaoperations.com/id/company/overview.

[37] IRENA Hydrogen From Renewable Power: Technology outlook for the energy transition, no. September. 2018.

[38] Jakobsen D and Åtland V 2016 Concepts for Large Scale Hydrogen Production Master Thesis 145 [Online]. Available: https://brage.bibsys.no/xmlui/handle/11250/2402554.

[39] Acar C and Dincer I 2013 Comparative environmental impact evaluation of hydrogen production methods from renewable and nonrenewable sources Causes, Impacts Solut. to Glob. Warm. 493–514

[40] “Neste invests 1.4b euros, builds new Singapore plant, Companies & Markets - THE BUSINESS TIMES.” https://www.businesstimes.com.sg/companies-markets/neste-invests-14b-euros-builds-new-singapore-plant (accessed Sep. 26, 2020).

[41] International Renewable Energy Agency - IRENA 2019 Future of solar photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects International Renewable Energy Agency, Abu Dhabi

[42] Gielen D, Taibi E, and Miranda R 2019 Hydrogen: a Renewable Energy Perspective September. 2019

[43] Cole W and Frazier A W 2019 Cost Projections for Utility- Scale Battery Storage Cost Projections for Utility- Scale Battery Storage doi: NREL/TP-6A20-73222.

[44] IRENA 2017 Technology Brief: Geothermal Power

[45] Khoon K L, Cobb A, and Harun M H 2011 The Potential of Oil Palm in the Global Carbon Cycle Palm Oil Dev. 54 8–13