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Optimization of Hydrogen Supply Chain: A Case Study in Malaysia

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Hydrogen is regarded as the fuel of future by having greater heating value than the conventional fuels and with zero carbon emission. Most of the previous supply chain studies only consider the application of hydrogen as transportation fuel. Taking Johor as a case study, this paper aims to develop a holistic optimization model that exploits the use of hydrogen for vehicle fueling and electricity generation. Oil palm biomass and solar energy are used as the energy sources to produce hydrogen and electricity to satisfy the local energy demand. Through this study, the optimal configuration of hydrogen supply chain in Johor has been identified and the associated cost is found to be 3,644,800 USD/d.

1. Introduction

The world energy demand has been elevating as a result of economic growth and development of global markets (Sáez-Martínez et al., 2016). Concurrently, the over-reliance on fossil fuels for energy generation has raised concerns regarding energy security and climate change. Thus, the transition of energy production from fossil fuels to renewable sources is crucial for a sustainable ecosystem. Numerous studies have been conducted to reduce the use of fossil resources by substituting with renewable energy supply, i.e. biomethane injection into natural gas distribution grid (Hoo et al., 2018) and biomass co-firing in coal-fired power plant (Mohd Idris, 2018). Hydrogen is an energy carrier that can be synthesized from both fossil resources and renewable resources (Palma et al., 2018). With its clean emission during combustion (Haron et al.,2017), hydrogen could serve as the fuel for fuel cell electric vehicles, fuel for combustion as well as electrical energy storage that stores the excess electricity generated from intermittent renewable sources (Mah et al., 2019).
For smooth operation of hydrogen-based energy system, the hydrogen supply chain (HSC) must be well planned. In recent studies, Kim and Kim (2016) developed an optimization model to design and analyze the hydrogen supply system using onshore and offshore wind energy. The onshore wind farms were more preferable than offshore farms due to lower capital investment, while centralized hydrogen production system was more superior over the distributed system owing to economy of scales. Reuß et al. (2017) investigated the use of liquid organic hydrogen carriers (LOHC) as seasonal hydrogen storage to balance the fluctuating renewable electricity generation and fuel demand. Through their study, LOHC would be a promising option if salt cavern storage for hydrogen remains uncompetitive. Won et al. (2017) formulated a MILP model by integrating multiple resources and technologies in which hydrogen is only produced from renewable energy sources (RES). The model was validated through a case study on Jeju Island and results showed that capital cost contributed the most significant part to the expenditure of RES-based HSC. While most of the previous studies focus on the application of hydrogen in the transportation sector, this paper aims to develop a holistic optimization model that considers the use of hydrogen for electricity generation in addition to the transportation fuel.

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2. Methodology

2.1 Hydrogen supply chain superstructure

The superstructure of hydrogen supply chain is illustrated in Figure 1, where the empty fruit bunches (EFB) and palm kernel shells (PKS) generated from palm oil mills serve as the raw materials of gasification process to produce hydrogen. Solar radiation will be collected through the photovoltaic (PV) panel and converted to electrical energy in the form of direct current. Inverter is used to convert electricity from direct current form into alternating current form. The electricity produced from solar radiation can be used to satisfy electricity demand of the district or converted into hydrogen via electrolysis. The hydrogen produced from gasification and electrolysis processes is stored in liquid form, which is then used to fulfill local hydrogen fuel demand or generate electricity through fuel cell to cater to the local electricity demand. Excess H_2 produced in a district can be exported to other districts that have insufficient energy supply.

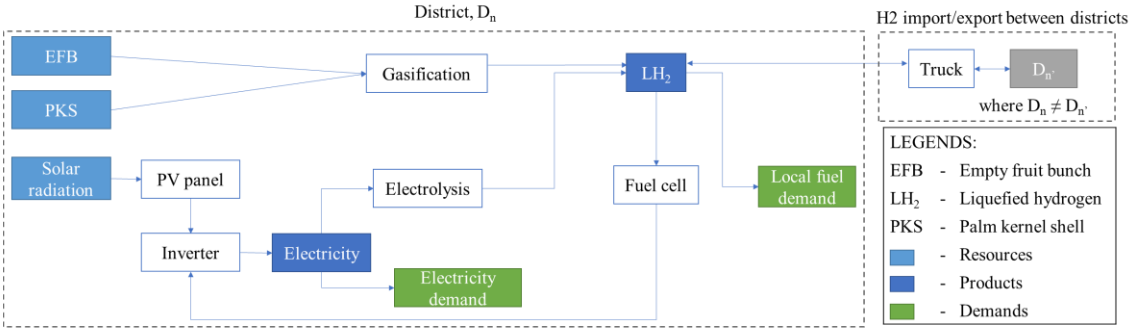

Figure 1: Superstructure of integrated hydrogen supply chain

2.2 Mathematical model

The mixed-integer linear programming (MILP) model in this work is extended from the model proposed by Almaraz et al. (2014), where PV system and fuel cell system have been incorporated into the model to consider the electricity generation from hydrogen and the interconversion between electricity and hydrogen.

2.2.1 Production constraints

Eq(1) represents the mass balance of hydrogen product in each district:

$$PT_{ig} = \sum_{l,g'}(Q_{ilgg'} - Q_{ilg'g}) + \left(H2_{ig}^{toe} - H2_{ig}^{frome}\right) + DT_{ig} \qquad \forall i,g;\ \ g \neq g' \tag{1}$$

where PT_{ig} is production rate of hydrogen form i in district g, $Q_{ilgg'}$ is amount of hydrogen form i delivered from district g to district g' through transportation mode l , $Q_{ilg'g}$ is amount of hydrogen form i delivered from district g' to district g through transportation mode l and DT_{ig} is the hydrogen fuel demand in form i in district g.
As shown in Eq(2), the total hydrogen production from biomass, PT_{ig} is equal to the sum of hydrogen produced from all types of production plants that utilize biomass as feedstock. Eq(3) illustrates that the capacity of each production plant should be within the lower and upper limits.

$$PT_{ig} = \sum_p PR_{pig} \quad \forall i,g \tag{2}$$

$$PCap_{pi}^{min} NP_{pig} \leq PR_{pig} \leq PCap_{pi}^{max} NP_{pig} \quad \forall p,i,g \tag{3}$$

where PR_{pig} is the production capacity of plant p producing hydrogen form i in district g, $PCap^{min}_{pi}$ is the minimum capacity of plant p producing hydrogen form i, $PCap^{max}_{pi}$ is the maximum capacity of plant p producing hydrogen form i and NP_{pig} is the number of plant p producing hydrogen form i in district g.

2.2.2 Transportation constraints

Eq(4) indicates the amount of hydrogen transported between districts should not violate the allowable limits. Eq(5) shows a district should not be exporting and importing hydrogen to/from the same district at a time.

$$Q_{il}^{min} X_{ilgg'} \leq Q_{ilgg'} \leq Q_{il}^{max} X_{ilgg'} \quad \forall i,l,g,g';\ \ g \neq g' \tag{4}$$

$$X_{ilgg'} + X_{ilg'g} \leq 1 \quad \forall i,l,g,g';\ \ g \neq g' \tag{5}$$

where Q^{min}_{il} is the minimum amount of hydrogen form i transported via transportation mode l, Q^{max}_{il} is the maximum amount of hydrogen form i transported via transportation mode l, $X_{ilgg'}$ is a binary determinant for the transportation of hydrogen form i via transportation mode l from district g to district g', and $X_{ilg'g}$ is a binary determinant for the transportation of hydrogen form i via transportation mode l from district g' to district g.

2.2.3 Storage constraints

Eq(6) shows the storage requirement of product and Eq(7) indicates the hydrogen product can be stored in tanks of different capacities. Eq(8) depicts the hydrogen stored in tanks should be within the allowable limits.

$$ST_{ig} = \beta\left(DT_{ig} + H2^{toe}_{ig}\right) \quad \forall i, g \tag{6}$$

$$ST_{ig} = \sum_s SI_{sig} \quad \forall i, g \tag{7}$$

$$SCap^{min}_{si} NS_{sig} \leq SI_{sig} \leq SCap^{max}_{si} NS_{sig} \quad \forall i, g \tag{8}$$

where ST_{ig} is the total inventory of product i in district g, β is the storage holding period, $SCap^{min}_{si}$ is the minimum storage capacity of hydrogen form i in storage unit s, $SCap^{max}_{si}$ is the maximum storage capacity of hydrogen form i in storage unit s, SI_{sig} is the hydrogen stored in form i in storage unit s in district g and NS_{sig} is the number of storage unit s storing hydrogen form i in district g.

2.2.4 PV system

The electricity produced from solar radiation is given in Eq(9). Eq(10) indicates the electricity generated from solar radiation can be used to fulfil the local electricity demand or converted to H_2. Eq(11) depicts the total electricity demand in a district can be satisfied by electricity produced from solar radiation and hydrogen.

$$E^S_g = R^S_g PV^A_g PV^{EFF} INV^{EFF} \quad \forall g \tag{9}$$

$$E^S_g = ED_g + E^{toH2}_g \quad \forall g \tag{10}$$

$$DET_g = ED_g + E^{fromH2}_g \quad \forall g \tag{11}$$

where E^S_g denotes the electricity produced from solar radiation in district g, R^S_g is the solar radiation in district g, PV^A_g is the area of PV panel in district g, PV^{EFF} is the efficiency of PV panel, INV^{EFF} is the efficiency of inverter, E^D_g is the amount of electricity transmitted to the demand site in district g, E^{toH2}_g is the amount of electricity converted to H_2 through electrolysis in district g, DET_g is the total electricity demand in district g, and E^{fromH2}_g is the amount of electricity produced from H_2 through fuel cell in district g.

2.2.5 Fuel cell system and electrolysis plant

The amount of electricity converted from H_2 is given by Eq(12). Eq(13) computes the yield of hydrogen in electrolysis process. The sum of hydrogen produced from each type of electrolysis plant should balance the total amount of hydrogen generated from electricity as illustrated in Eq(14). Eq(15) shows the production capacity of electrolysis plant is bounded by its lower and upper production limits.

$$E^{fromH2}_g = \sum_i H2^{toE}_{ig} Y^{H2toE} INV^{EFF} \quad \forall g \tag{12}$$

$$\sum_i H2^{frome}_{ig} = E^{toH2}_g Y^{EtoH2} \quad \forall g \tag{13}$$

$$H2^{frome}_{ig} = \sum_e PE_{eig} \quad \forall i, g \tag{14}$$

$$ECap^{min}_{ei} NE_{eig} \leq PE_{eig} \leq ECap^{max}_{ei} NE_{eig} \quad \forall e, i, g \tag{15}$$

where $H2^{toE}_{ig}$ is the amount of hydrogen form i converted to electricity in district g and Y^{H2toE} is yield of electricity per unit hydrogen reacted in fuel cell, Y^{EtoH2} is yield of H_2 per unit electricity consumed and PE_{eig} is production rate of hydrogen form i at electrolysis plant e in district g, $ECap^{min}_{ei}$ is the minimum capacity of electrolysis plant e producing hydrogen form i, $ECap^{max}_{ei}$ is maximum capacity of electrolysis plant e producing hydrogen form i and NE_{eig} is the number of electrolysis plant e producing hydrogen form i in district g.

Eq(16) and (17) indicate that the capacity of inverter is dependent on the amount electricity from PV panel or fuel cell, whichever is greater. Meanwhile, the capacity of fuel cell is dependent on the electricity throughput as shown in Eq(18).

$$INV_g^{CAP} \geq \frac{E_g^S}{H^S\, INV^{EFF}} \quad \forall g \tag{16}$$

$$INV_g^{CAP} \geq \frac{E_g^{fromH2}}{H^S\, INV^{EFF}} \quad \forall g \tag{17}$$

$$FC_g^{CAP} \geq \frac{E_g^{fromH2}}{H^S\, FC^{EFF} INV^{EFF}} \quad \forall g \tag{18}$$

where $INV^{CAP}{}_g$ is inverter capacity in district g, H^S is peak sun hours, $FC^{CAP}{}_g$ is fuel cell capacity in district g.

2.2.6 Objective function

The objective function of this model is to minimize the total daily cost of HSC which is defined in Eq(19). Eq(20) and (21) represents the mathematical expression for facility capital cost and operating cost.

$$TDC = \frac{FCC + TCC}{\alpha \cdot CCF} + FOC + TOC \tag{19}$$

$$FCC = \sum_g \left[\sum_i \left(\sum_p PCC_{pi} NP_{pig} + \sum_s SCC_{si} NS_{sig} + \sum_e ECC_{ei} NE_{eig}\right) + PV_g^A\, PV^{EFF} PVCC + FC_g^{CAP}\, FCCC + INV_g^{CAP}\, INVCC\right] \tag{20}$$

$$FOC = \sum_g \left[\sum_i \left(\sum_p UPC_{pi} PR_{pig} + \sum_s USC_{si} SI_{sig} + \sum_e UEC_{ei} PE_{eig}\right) + PV_g^A\, PV^{EFF} PVUC + FC_g^{CAP}\, FCUC\right] \tag{21}$$

where TDC is total daily cost, FCC is facility capital cost, TCC is transportation capital cost, FOC is facility operating cost, TOC is transportation operating cost, α is network operating period, CCF is capital change factor, PCC_{pi} is capital cost of production technology p producing hydrogen form i, SCC_{si} is capital cost of storage unit s for hydrogen form i, ECC_{ei} is capital cost of electrolysis plant e producing hydrogen form i, PVCC is unit capital cost of PV system, FCCC is unit capital cost of fuel cell, INVCC is unit capital cost of inverter, UPC_{pi} is unit production cost of production plant p producing hydrogen form i, USC_{si} is unit storage cost of storage unit s for hydrogen form i, UEC_{ei} is unit electrolysis cost for electrolysis plant e producing hydrogen form i, PVUC is unit operating cost of PV system, FCUC is unit operating cost of fuel cell system.
Eq. (22) and (23) represent the mathematical expressions for transportation capital cost:

$$NTUgrid_{ilgg'} = \left[\frac{Q_{ilgg'}}{TMA_l TCap_{il}}\left(\frac{2AD_{gg'}}{SP_l} + LUT_l\right)\right] \quad \forall i, l, g, g' \tag{22}$$

$$TCC = \sum_{ilgg'} NTUgrid_{ilgg'}\, \mathrm{TMC_{il}} \tag{23}$$

where $NTUgrid_{ilgg'}$ is the number of transportation unit carrying hydrogen form i via transportation mode l from district g to district g', TMA_l is availability of transportation mode l, $TCap_{il}$ is capacity of transportation mode l carrying hydrogen form i, $AD_{gg'}$ is the average distance between district g and g', SP_l is the mean speed of transportation mode l, LUT_l is the load and unload time for transportation mode l, and TMC_{il} is the cost of establishing transportation mode l transporting hydrogen form i.
Eq (24) to (28) show the calculations for transportation operating cost:

$$FC = \sum_{ilgg'} FP_l \left(\frac{2AD_{gg'} Q_{ilgg'}}{FE_l TCap_{il}}\right) \tag{24}$$

$$LC = \sum_{ilgg'} DW_l \left[\frac{Q_{ilgg}}{TCap_{il}}\left(\frac{2AD'_{gg}}{SP_l} + LUT_l\right)\right] \tag{25}$$

$$MC = \sum_{ilgg'} ME_l \left(\frac{2AD_{gg'} Q_{ilgg'}}{TCap_{il}}\right) \tag{26}$$

$$GC = \sum_{ilgg'} GE_l \left[\frac{Q'_{ilgg}}{TMA_l TCap_{il}}\left(\frac{2AD'_{gg}}{SP_l} + LUT_l\right)\right] \tag{27}$$

$$TOC = FC + LC + MC + GC \tag{28}$$

where FC is fuel cost, LC is labour cost, MC is maintenance cost, GC is general cost, FP_l is the fuel price of transportation mode l, FE_l is the fuel economy for transportation mode l, DW_l is the driver wage of transportation mode l, ME_l is the maintenance expenses for transportation mode l, GE_l is the general expenses for transportation mode l.

3. Case study

In this work, the optimization of HSC is performed on Johor region which is geographically divided into 10 districts. Table 1 shows the availability of energy resources and energy demand of the districts, where the fuel and electricity of each district are estimated using its population as illustrated in Eq(29) and (30). The optimal HSC configuration determined from the optimization result is illustrated in Figure 2.

$$Electrcity\ demand\ of\ district = \frac{National\ electricity\ demand \times Population\ in\ district}{National\ population} \tag{29}$$

$$District\ fuel\ demand = \frac{Number\ of\ vehicle\ in\ Johor \times District\ population}{Johor\ population} \times Average\ distance\ travelled \times Fuel\ economy\ of\ hydrogen \tag{30}$$

The vehicle number in Johor and the average distance travelled is obtained from Shabadin et al. (2014), the national electricity demand is obtained from Malaysia Energy Commission (2018), the national and regional population is retrieved from Department of Statistics Malaysia (2010), and the fuel economy of fuel cell vehicle is assumed to be 0.76 kg/100 km, the same as Toyota Mirai (Toyota Motor Europe, 2015). For solar system, the information for PV panel and inverter is obtained from Elshurafa et al. (2019), the average solar radiation in the districts is extracted from Meteoblue (2019) and peak sun hours is assumed to be 4 hours per day. The capital and operating cost of fuel cell is 434 USD/kW and 0.05 USD/kW·d (Steward et al., 2009). Information for production, storage, transportation and capital change factor is adapted from Almaraz et al (2014).

Table 1: Transportation fuel and electricity demand of the districts

No.	District	Solar radiation (kWh/d)	EFB supply (kg/d)	PKS supply (kg/d)	Fuel demand (kg H_2/d)	Electricity demand (kWh/d)
1	Batu Pahat	4.29	424,110	96,389	48,979	4,917,749
2	Johor Bahru	4.89	29,589	6,725	162,604	16,325,378
3	Kluang	4.29	1,692,493	384,658	35,146	3,528,477
4	Kota Tinggi	5.03	1,147,068	260,697	22,894	2,298,250
5	Mersing	4.51	230,538	52,395	8,415	844,640
6	Muar	4.35	345,205	78,456	29,140	2,924,780
7	Pontian	4.89	24,658	5,604	18,280	1,834,670
8	Segamat	4.58	1,010,959	229,763	22,311	2,239,039
9	Ledang	4.55	36,986	8,406	16,082	1,613,831
10	Kulaijaya	4.89	355,068	80,697	29,901	3,001,464

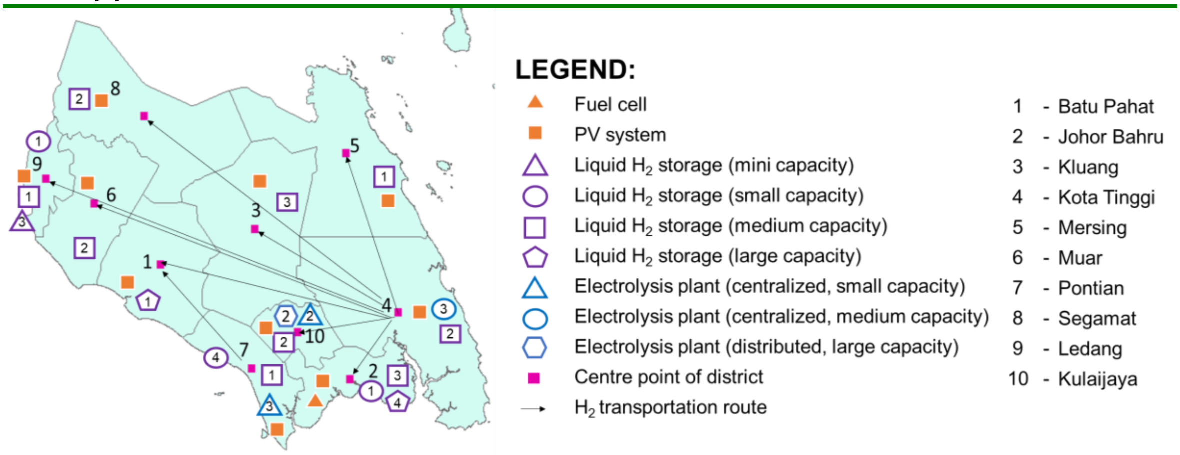

Figure 2: Optimal HSC configuration

The optimization model in GAMS was run in Windows 10 Pro 64-bit operating system with Intel(R) Core(TM) i5-6200U CPU @ 2.30GHz 2.40GHz and 8GB installed RAM. The CPU time taken to solve the model with 51 variables was 43s. Through GAMS optimization, the optimal cost of HSC is determined to be 3,644,800 USD/d. From Figure 2, it can be observed that all districts will employ PV system and 3 of the districts will be having electrolysis plant. No gasification plant is used meaning that the all hydrogen will be produced from electrolysis process. By having higher intensity of solar radiation and lower energy demand, Kota Tinggi could potentially be a large exporter of hydrogen followed by Pontian, while other districts will be the hydrogen importer. Fuel cell system is only found in Johor Bahru, which is the district with the greatest energy demand.

4. Conclusions

The model proposed in this paper extends the use of hydrogen to fulfil the fuel and electricity demand, and the interconversion between hydrogen and electricity is being modelled. This work is significant in exploring the roles of hydrogen in future energy system, and future study should consider the spatial planning of facilities.

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