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Hydrogen Supply Chain Optimisation with Green Electricity Generation for Energy Trading Between Industrial Parks

Muhammad Fakhri Salahuddin Ahmad Fadhil[a], Peng Yen Liew[a,*], Hazirah Hanim Zaharuddin[a], Angel Xin Yee Mah[b], Wai Shin Ho[c], Kok Sin Woon[d]

[a]Department of Chemical and Environmental Engineering, Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia (UTM) Kuala Lumpur, Jalan Sultan Yahya Petra, 54100 Kuala Lumpur, Malaysia
[b]NUS Environmental Research Institute, National University of Singapore, 138602, Singapore
[c]Faculty of Chemical and Energy Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia
[d]School of Energy and Chemical Engineering, Xiamen University Malaysia, Jalan Sunsuria, Bandar Sunsuria, 43900 Sepang, Selangor, Malaysia
pyliew@utm.my

Hydrogen can complement renewable energy to produce green electricity and green hydrogen. Most supply chain studies do not consider hydrogen demand in industrial zones and have never considered hydrogen as an energy source to meet industry's energy needs. This paper develops an optimal Hydrogen Supply Chain (HSC) network to minimise the overall cost of the energy system, considering the energy trading option across industrial zones. Grey and blue hydrogen are included with natural gas as the Steam Methane Reforming (SMR) plant feedstock and SMR with the Carbon Capture Storage (CCS) plant. Green electricity production from solar, wind, hydroenergy, and biomass gasification are considered to produce green hydrogen in this study. Through AIMMS modelling and optimisation, it was determined that the total daily cost (TDC) of the HSC network is 2,464 million USD/d. Hydrogen trading is essential to minimise the energy consumption of hydrogen production plants. Hydrogen trading is forcing one industrial zone with excess hydrogen to export to other industrial zones with insufficient hydrogen to meet its energy demand. In simple terms, hydrogen trading does not fully rely on hydrogen production plants but relies on transportation technology to import and export hydrogen for other industrial zones. With that, hydrogen trading can minimise the TDC of the HSC network and minimise the energy consumption from conventional hydrogen production plants. According to the results, the main exporter of hydrogen is industrial zone G2, with 115.57 t/d of hydrogen.

1. Introduction

Many countries focus on developing a more sustainable and clean energy supply by exploring and getting more low-carbon and renewable energy sources, such as solar, wind, hydro and geothermal. Reliance on fossil fuels increases greenhouse gas (GHG) emissions and causes climate change. The transition of energy systems from fossil-based to renewable energy is essential for sustainable development. Hydrogen is a critical player in the energy transition due to its potential as a clean and sustainable energy carrier (Guilbert and Vitale, 2021). Hydrogen could decarbonise the energy sector through its utilisation as fuel cell EV fuel, energy storage, and power generation. Hydrogen is a potential future fuel as it has a clean emission with high gravimetric energy density (Mah et al., 2020). Despite being an important feedstock for the chemical industry, it can also be a suitable energy storage medium compared to conventional batteries.

A hydrogen supply chain (HSC) network comprises four influential echelons: production, storage, transportation, and distribution. The shift to a hydrogen economy highly depends on the HSC, which presents opportunities and constraints differently. Sgarbossa et al. (2023) give the planning and outline for a cleaner hydrogen supply chain network to support renewable energy development. Corresponding to demand fluctuation, Yoon et al. (2022) improved the research by considering multi-period optimisation of the HSC network. Erdoğan and Güler (2023) applied the model for a case study in Turkey. These studies include all possible hydrogen production

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technologies to see the optimal pathway to produce hydrogen. To improve the current studies, the capital cost can be eliminated using the current natural gas pipelines and infrastructure to minimise the total daily cost of the HSC network.

However, none of these studies consider the need for green electricity and hydrogen fuel in industrial zones to meet the energy demand. Although energy management has its optimisation strategy, optimising the hydrogen supply chain can also be considered one of the solutions to minimise energy consumption. While previous research has primarily focused on utilising hydrogen in the transportation industry, this paper takes a different approach. This study develops an optimisation model to quantify the potential use of hydrogen to fulfil the energy demand of several industrial zones through hydrogen trading and green electricity-based hydrogen production.

2. Methodology

2.1 Superstructure of the hydrogen supply chain

The feedstock for hydrogen production comes from natural gas, biomass, and solar energy. The feedstock selected is based on their availability in Malaysia. Natural gas is a source for large petrochemical plants, while biomass such as empty fruit bunches (EFB) will be used for gasification. Solar energy harvested using PV panels will be used as an electricity source for electrolysis to produce green hydrogen. Wind energy considers the velocity of wind, while hydro-energy considers the flow rate of water as a source to generate green electricity. The green electricity from these renewable sources will fulfil hydrogen and electricity demand in each industrial zone. The superstructure of the HSC network for this study is illustrated in Figure 1.

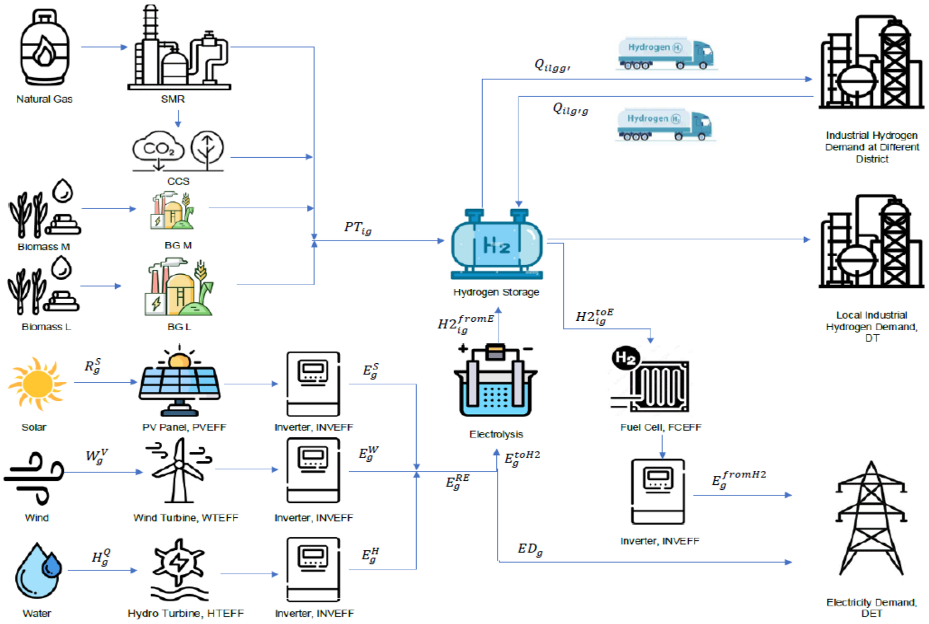

Figure 1: Generic superstructure of hydrogen supply chain with green electricity generation

2.2 Mathematical modeling

The mixed integer linear programming (MILP) is extended from Mah et al. (2020), where all possible hydrogen production technologies available in Malaysia were considered for electricity generation from hydrogen and renewable energy.

2.2.1 Production and Trading Constraints

The mass balance of hydrogen production in the HSC network is represented in Eq.(1).

$$PT_{ig} = \sum_{lg'} (Q_{ilgg'} - Q_{ilg'g}) + (H2_{ig}^{toE} - H2_{ig}^{fromE}) + DT_{ig} \qquad \forall\, i, g; g \neq g' \tag{1}$$

Where PT_{ig} is the total production of hydrogen in form *i* in industrial zone *g*, $Q_{ilgg'}$ is the amount of hydrogen form *i* delivered from industrial zone *g* to industrial zone *g'* through transportation mode *l*, $Q_{ilg'g}$ is the amount of hydrogen form *i* exported from industrial zone *g'* to industrial *g* through transportation mode *l*, and DT_{ig} is the hydrogen demand in form *i* in industrial zone *g*. As shown in Eq(2), the total hydrogen production from steam methane reforming (SMR), SMR with carbon capture storage (CCS) and biomass gasification, PT_{ig} is equal to the sum of hydrogen produced from all types of production plants that utilise natural gas and biomass as feedstock. The hydrogen production rate, PR_{pig} is constrained with minimum and maximum capacities, as shown in Eq(3).

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

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

where NP_{pig} is the number of hydrogen plant p producing hydrogen form *i* in industrial zone *g*, $PCap_{pi}^{min}$ is the minimum capacity of hydrogen plant *p* producing hydrogen form *i*, while $PCap_{pi}^{max}$ is the maximum capacity of hydrogen plant *p* producing hydrogen form *i*.

2.2.2 Storage constraints

The storage capacity of the hydrogen is represented in Eq(4). Eq(5) shows the different types of hydrogen storage capacity, and Eq(6) represents that hydrogen stored should be constrained with allowable limits.

$$ST_{ig} = \beta(DT_{ig} + H2_{ig}^{toE} + \sum_{lg'}(Q_{ilgg'}) \qquad \forall\, i, g \tag{4}$$

$$ST_{ig} = \sum_s SI_{sig} \qquad \forall\, i, g \tag{5}$$

$$SCap_{si}^{min} NS_{sig} \leq SI_{sig} \leq SCap_{pi}^{max} NS_{sig} \qquad \forall\, p, i, g \tag{6}$$

where ST_{ig} is the total hydrogen produced in the form *i* in industrial zone *g* and *β* is the storage holding period. $SCap_{si}^{min}$ is the minimum capacity of hydrogen produced in the form *i* stored in storage *s*, while $SCap_{si}^{max}$ is the maximum hydrogen storage capacity in the form *i* stored in storage *s*. NS_{sig} is the amount of storage used to store hydrogen form *i* in storage *s* in industrial zone *g*.

2.2.3 Transportation constraints

The hydrogen transported between industrial zones for hydrogen trading must be within the allowable limits is represented in Eq(7). Eq(8) indicates that one industrial zone cannot simultaneously receive and send hydrogen from/to an industrial zone at a time.

$$Q_{il}^{min} X_{ilgg'} \leq Q_{ilgg'} \leq Q_{il}^{max} X_{ilgg'} \qquad \forall i, l, g, g'; g \neq g' \tag{7}$$

$$X_{ilgg'} + X_{ilg'g} \leq 1 \qquad \forall i, l, g, g'; g \neq g' \tag{8}$$

where Q_{il}^{min} is the minimum amount of hydrogen form *i* through transportation mode *l*, while Q_{il}^{max} is the maximum amount of hydrogen form *i* through transportation mode *l*. $Q_{ilgg'}$ is the flow rate of hydrogen form *i* transported via transportation mode *l* from industrial zone g to industrial zone *g'*. $X_{ilgg'}$ is the binary determinant for hydrogen in form *i* transportation via transportation mode l from industrial zone g to industrial zone *g'*, while $X_{ilg'g}$ is the binary determinant for hydrogen in form *i* transportation via transportation mode *l* from industrial zone *g'* to industrial zone *g*.

2.2.4 Green electricity system

The green electricity produced from solar, wind and hydro energy are represented in Eqs.(9-11). Eq(12) shows the total green electricity produced from renewable energy.

$$E_g^S = \mathrm{R_g^S}\, \mathrm{PV_g^A}\, PV^{EFF}\, INV^{EFF} \qquad \forall\, g \tag{9}$$

$$E_g^w = 0.5\mathrm{Cp}\rho_a \mathrm{R}^2 {W_g^V}^3\, INV^{EFF} \qquad \forall\, g \tag{10}$$

$$E_g^H = H_g^Q \rho_w \mathrm{gH} HT^{EFF}\, INV^{EFF} \qquad \forall\, g \tag{11}$$

$$E_g^{RE} = E_g^S + E_g^w + E_g^H \qquad \forall\, g \tag{12}$$

where E_g^S is the solar energy, E_g^w is the wind energy and E_g^H is hydro energy. For solar energy, R_g^S is solar radiation, PV_g^A is the area of PV panel, PV^{EFF} is the PV efficiency and INV^{EFF} is the inverter efficiency. For wind energy, *Cp* is the coefficient of performance, ρ_a is air density, *R* is the blade length, and W_g^V is the wind speed.

For hydro energy, H_{g}^{Q} is flowrate of water, ρ_w is water density, H is the height of the damp, and HT^{EFF} is the hydro turbine efficiency.

Eq(13) shows that renewable energy can be used to meet the demand for electricity in industrial zones or converted to H_2. Eq(14) indicates the industrial zone electricity demand that can be satisfied by green electricity and hydrogen electrolysis.

$$E_g^{RE} = ED_g + E_g^{toH2} \qquad \forall g \tag{13}$$

$$DET_g = ED_g + E_g^{fromH2} \qquad \forall g \tag{14}$$

where ED_g is the green electricity generated, and DET_g is the total industrial zone electricity demand. E_g^{toH2} is the amount of electricity used in industrial zone g to produce hydrogen and E_g^{fromH2} is the amount of green hydrogen produced in industrial zone g.

2.2.5 Fuel cell and electrolysis system

The amount of electricity converted from H_2 is shown in Eq(15). Eq(16) indicates the yield of the electrolysis process. The sum of hydrogen produced from each electrolysis plant should balance the total hydrogen generated from electricity, as illustrated in Eq(17). Eq(18) represents the capacity of an electrolysis plant bound by its lower and upper production limits.

$$E_g^{fromH2} = \textstyle\sum_i H2_{ig}^{toE}\, Y^{H2toE}\, INV^{EFF} \qquad \forall g \tag{15}$$

$$\textstyle\sum_i H2_{ig}^{fromE} = E_g^{toH2}\, Y^{EtoH2} \qquad \forall g \tag{16}$$

$$H2_{ig}^{fromE} = \textstyle\sum_e PE_{eig} \qquad \forall i, g \tag{17}$$

$$ECap_{ei}^{min} NE_{sig} \leq PE_{eig} \leq ECap_{pi}^{max} NE_{eig} \qquad \forall\, e, i, g \tag{18}$$

where $H2_{ig}^{toE}$ is hydrogen form i converted to electricity in industrial zone g and Y^{H2toE} is the yield of hydrogen converted to electricity through fuel cells. Y^{EtoH2} is the yield of hydrogen produced per electricity consumed through electrolysis. The production rate of hydrogen form i at electrolysis plant e in industrial zone g, PE_{eig} is bounded within the minimum, $ECap_{ei}^{min}$ and maximum, $ECap_{pi}^{max}$ indicates the maximum of the plant's capacity. NE_{eig} is the number of electrolysis plants e producing hydrogen form i in industrial zone g.

2.2.6 Objective function

The objective function of this case study is shown in Eq(19), which is to minimise the total daily cost of the HSC network. Eqs. (20-21) shows facility operating and capital costs.

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

$$\begin{aligned} FOC = \textstyle\sum_g \big[\textstyle\sum_i \big(\textstyle\sum_p (UPC_{pi} + FSP_p) PR_{pig} + \textstyle\sum_s USC_{si} SI_{sig} + \textstyle\sum_e UEC_{ei} PE_{eig} \big) + PV_g^{A}\, PV^{EFF}\, PVUC + \\ FC_g^{CAP}\, FCUC \big] \end{aligned} \tag{20}$$

$$\begin{aligned} FCC = \textstyle\sum_g \big[\textstyle\sum_i \big(\textstyle\sum_p PCC_{pi} NP_{pig} + \textstyle\sum_s SCC_{si} NS_{sig} + \textstyle\sum_e ECC_{ei} NE_{eig} \big) + PV_g^{A}\, PV^{EFF}\, PVCC + \\ FC_g^{CAP}\, FCCC + INV_g^{CAP}\, INVCC \big] \end{aligned} \tag{21}$$

where *TDC* is total daily cost, *FCC* is facility capital cost, *TCC* is transportation capital cost, *α* is network operating period, *FOC* is facility operating cost, and *TOC* is transportation operating cost. *CCF* is the capital change factor, which refers to the payback period of capital investment. UPC_{pi} is the unit production cost of hydrogen plant *p* producing hydrogen form *i*, FSP_p is the feedstock price of hydrogen plant p, USC_{si} is the unit storage cost of storage unit *s* for hydrogen form *i*, UEC_{ei} is the 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 the fuel cell system. PCC_{pi} is the capital cost of hydrogen plant *p* producing hydrogen form *i*, SCC_{si} is the capital cost of storage unit *s* for hydrogen form *i*, ECC_{ei} is the capital cost of electrolysis plant *e* producing hydrogen form *i*, *PVCC* is the PV system's capital cost, *FCCC* is the fuel cell's capital cost, *INVCC* is the inverter's capital cost.

The transportation capital cost is shown as follows:

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

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

where *NTUgrid*$_{ilgg'}$ is the number of transportation units of hydrogen form *i* via transportation mode *l* from industrial zone *g* to *g'*, *TMA*$_l$ is the availability of transportation mode *l*, *TCap*$_{il}$ is capacity of transportation *l* carrying hydrogen form *i*, *AD*$_{gg'}$ is the distance between industrial zone *g* to *g'*, *SP*$_l$ is the average speed of transportation mode *l*, *LUT*$_l$ is the load/ unload time for transportation mode *l*, and *TMC*$_{il}$ is the unit cost of transportation mode *l* carrying hydrogen form *i*.

Eqs(24-28) indicate the component in transportation operating cost.

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

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

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

$$GC\ = \sum_{ilgg'} GE_l\ [\frac{Q_{ilgg'}}{TMA_l TCap_{il}}(\frac{2AD_{gg'}}{SP_l} + LUT_l)] \tag{27}$$

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

where *FC* is the fuel cost, *LC* is the labour cost, *MC* is the maintenance cost, *GC* is the general cost. *FP*$_l$ is the fuel price of transportation mode *l*, *FE*$_l$ is the fuel economy of transportation mode *l*. *DW*$_l$ is the drive wages, *LUT*$_l$ is the loading and unloading time of transportation mode *l*, *SP*$_l$ is the average speed of transportation mode *l*, *ME*$_l$ is the maintenance expenses, and *GE*$_l$ is general expenses, which include transportation mode *l* insurance, license and registration.

3. Case Study

The case study has eight industrial zones across Peninsular Malaysia; the industrial areas are assumed to have the capacity to generate grey, blue, and green hydrogen and green electricity to support the energy demand. The industrial zones can import and export hydrogen energy to minimise overall energy consumption. The hydrogen demand for eight industrial zones is estimated (Neuwirth et al., 2022). The natural gas price is obtained from BEIS UK (2021), which produces 1.25 USD/kg H_2. Biomass prices for medium-scale and large-scale plants were obtained from Cook and Hagen (2024), which are 2.00 USD/kg H_2 produced and 4.00 USD/kg H_2 produced. The fuel economy of transportation mode *l*, truck, is 2.3 km/L of diesel used (Webfleet, 2020). The data on the PV system is assumed based on Elshurafa et al. (2019), and the PV area is assumed to be 1 % of the industrial zone area. Wind power and hydropower energy sources are not considered in the case study because wind power is not feasible in the studied regions. Hydropower is commonly connected to the national power grid, where industrial zones cannot operate any hydropower plant. Table 1 outlines the energy demand and parameters used. The MILP model is solved in Windows 11 Pro 64-bit operating system MSI machine with Intel(R) Core(TM) i5-12450H CPU @ 2.00GHz to 4.40GHz and 16GBDDR5 by using BARON solver accessed with AIMMS version 24.2.1.0. The CPU time to solve the model with 581 variables and 797 constraints is 11.55 s. Through AIMMS optimisation, the optimal total daily cost of HSC is determined to be 2,464 M USD/d.

Table 1 Energy demands for each industrial zone

No	Industrial Zone	Solar radiation (kWh/d)	PV area (m^2)	Electricity demand (kWh/d)	H_2 demand (kg/d)
G1	Pasir Gudang	3,596,000	4.45	46,608,676	502,420
G2	Pengerang	34,840,000	4.454	19,983,827	1,355,629
G3	Kulai	7,560,000	4.477	29,648,352	153,893
G4	Melaka	16,520,000	4.684	89,704,599	989,609
G5	Port Dickson	6,050,000	4.878	11,585,207	1,495,710
G6	Klang	6,270,000	4.731	98,897,683	192,367
G7	Kemaman	25,360,000	4.815	19,783,029	695,889
G8	Kuantan	29,600,000	4.929	49,405,190	167,685

According to the optimisation results, eight hydrogen plants are in different industrial zones. However, it is worth noting that there are only two electrolysis plants, specifically at G2 and G7. The production technology for eight industrial zones primarily relies on steam methane reforming plants due to the lower cost of natural gas as a feedstock than biomass. The main industrial zones that produce green hydrogen from green electricity through electrolysis are G2 and G7. The electrolysis plant will only be operational if extra energy is available after meeting the electricity demands of the nearby industrial zone. The primary importer for the HSC network is G6 (Klang), which receives 102.5 t/d of hydrogen. The main exporter for this HSC network is G2 (Pengerang), which distributes hydrogen to G3 and G6 with a total of 115.57 t/d of hydrogen because G2 has excess hydrogen after satisfying local energy demand. In this case, each industrial zone has its production plant to fulfil the energy demand. Apart from that, the G8 industrial zone can stand on its own. Despite that, hydrogen trading is essential to minimise the TDC. When the TDC is minimised, energy reduction is also applied since the hydrogen plant consumes more energy than distributing hydrogen by using transportation such as trucks.

Table 2 Hydrogen trading network between industrial zones

Sender Receiver	G1 - Pasir Gudang (kg/d)	G2 - Pengerang (kg/d)	G4 - Melaka (kg/d)	G5 - Port Dickson (kg/d)	G7 - Kemaman (kg/d)
G3 - Kulai		77,580			
G6 - Klang	10,985	37,989	20,382	27,298	5,845

4. Conclusions

The model presented in this paper shows the application of hydrogen energy to meet the demand for hydrogen fuel and electricity in the industrial zones, focusing on modelling the conversion of hydrogen energy from green, blue and grey resources. The model can optimise the supply chain for an industrial zone and determine the hydrogen energy trading network across industrial zones. This research is essential in investigating the industry's potential in hydrogen energy. Future research must be conducted as a guideline and framework for Malaysia to achieve a hydrogen economy.

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