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Spatial Planning of Photovoltaic-Based Hydrogen Supply Chain: Optimal Site Location and Supply Chain Operation

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The transition of energy system from fossil-based to low-carbon based is crucial for sustainable development. Hydrogen is a potential fuel of the future as it has a clean emission aside with high gravimetric energy density. To minimise the cost of the future hydrogen supply network, the location of hydrogen production site should be well-selected. While most of the past studies have employed mathematical model to optimise the hydrogen supply chain, spatial conditions such as availability of energy sources, transportation network and land-use should also be considered when identifying the optimal site location. This study proposes a two-stage spatially-explicit hydrogen supply chain optimisation framework that integrates the Geographical Information System and mathematical optimisation model. The first stage involves spatial analysis to identify potential production site and demand site locations based on the geographical factors. Transportation distance between the potential production sites and the demand sites will be computed and input to the mathematical optimisation model. In the second stage, the mathematical model is solved to identify the cost-optimal production site location. The proposed methodology is applied to Malaysia case study and the optimal site location has been identified. The annual cost of the optimised hydrogen supply chain is determined to be 159.3 million USD.

1. Introduction

Rapid economic growth in the world is closely linked with increased global energy demand (Sáez-Martínez et al., 2016), which raises concerns about energy security and climate change. In comparison to conventional fuels, hydrogen is an attractive energy carrier as it is carbon-free with high energy density by weight (Acar and Dincer, 2018). Hydrogen could decarbonize the energy use through its potential applications as automobile fuel, energy storage and electricity supply. The network of facilities involved in the synthesis, storage, and distribution of hydrogen is commonly named as hydrogen supply chain (HSC). For a feasible hydrogen economy, the cost of HSC should be minimised while satisfying the needs. This requires the location of production hubs to be optimised as well as the hydrogen production, storage and transportation capacities.

Mathematical models are the most commonly employed methods in designing and modelling the HSC. Won et al. (2017) formulated a MILP model in which hydrogen was solely produced from renewable energy sources and the model was validated through a case study on Jeju Island. Moreno-Benito et al. (2017) extended the optimisation-based framework SHIPMod for the design of the HSC. The extended framework allows a quantitative evaluation of the infrastructure components at different phases of the transition towards a sustainable low-carbon hydrogen economy. Meanwhile, some studies optimised HSC based on multiple objective functions. Almaraz et al. (2014) presented a multi-period and multi-objective optimisation model to access the feasibility of HSC in France region based on economic, environmental and safety factors over the period of 2020-2050. Ogumerem et al. (2018) developed a multi-objective model to simultaneously maximise the net present value of HSC and minimise the greenhouse gases emission. The model is applied to Texas case study and two scenarios have been evaluated: i) vent the oxygen produced from electrolysis into the atmosphere or ii) collect, compress and sell the oxygen for revenue.

A geographic information system (GIS) is a framework for gathering, managing and analysing spatial data. GIS-based method for modelling HSC network is not generic but dependent on the specific conditions at a national or regional scale such as transportation network and population. The integration of mathematical optimisation

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and GIS model can complement the strengths of both methods as the mathematical model allows complex modelling of HSC and GIS takes into account the spatial conditions (Dagdougui, 2012). For instance, Almaraz et al. (2015) employed GIS for pre- and post-optimisation stages. The pre-optimisation stage involves spatial data treatment where the production plants and refuelling stations are located and the delivery distance between main cities is being computed. For the post-optimisation stage, the optimisation results are visualised on the map. Samsatli and Samsatli (2019) employed GIS for site suitability modelling to calculate the area available for wind turbine installation in each zone considering the spatial constraints such as economic zone coverage, distance to shipping routes, and water depth.

While many HSC studies have been done for other countries, the HSC study for Malaysia is still at an infancy stage. Mah et al. (2020) proposed a mathematical model for the optimisation of HSC in Johor, Malaysia but the geographical constraints are not taken into account. This study aims to develop a spatially-explicit HSC optimisation framework that integrates the optimisation model with GIS to optimise the future HSC in Malaysia and determine the optimal production site location. For this study, the production of hydrogen from solar energy is considered, thus the spatial solar irradiance will be taken into account when determining the optimal production site location in addition to the aforementioned geographical factors. To the best of the authors' knowledge, no similar study has been done to determine the optimal location of solar-based hydrogen production site through spatial optimisation of HSC. The selection of production site location is crucial to have low investment cost and smooth product logistics.

2. Methodology

Fig. 1 shows the proposed methodology which is a combination of spatial analysis and mathematical optimisation. The potential location of hydrogen production hubs and the location of demand sites will be first determined through spatial data processing in ArcGIS. The distance between potential processing sites and demand sites will be computed and input to the mathematical optimisation model for hub selection. The mathematical model considers factors such as solar irradiance, transportation distance, and technology cost when determining the best hub location and also the capacity of production, storage, and transportation facilities.

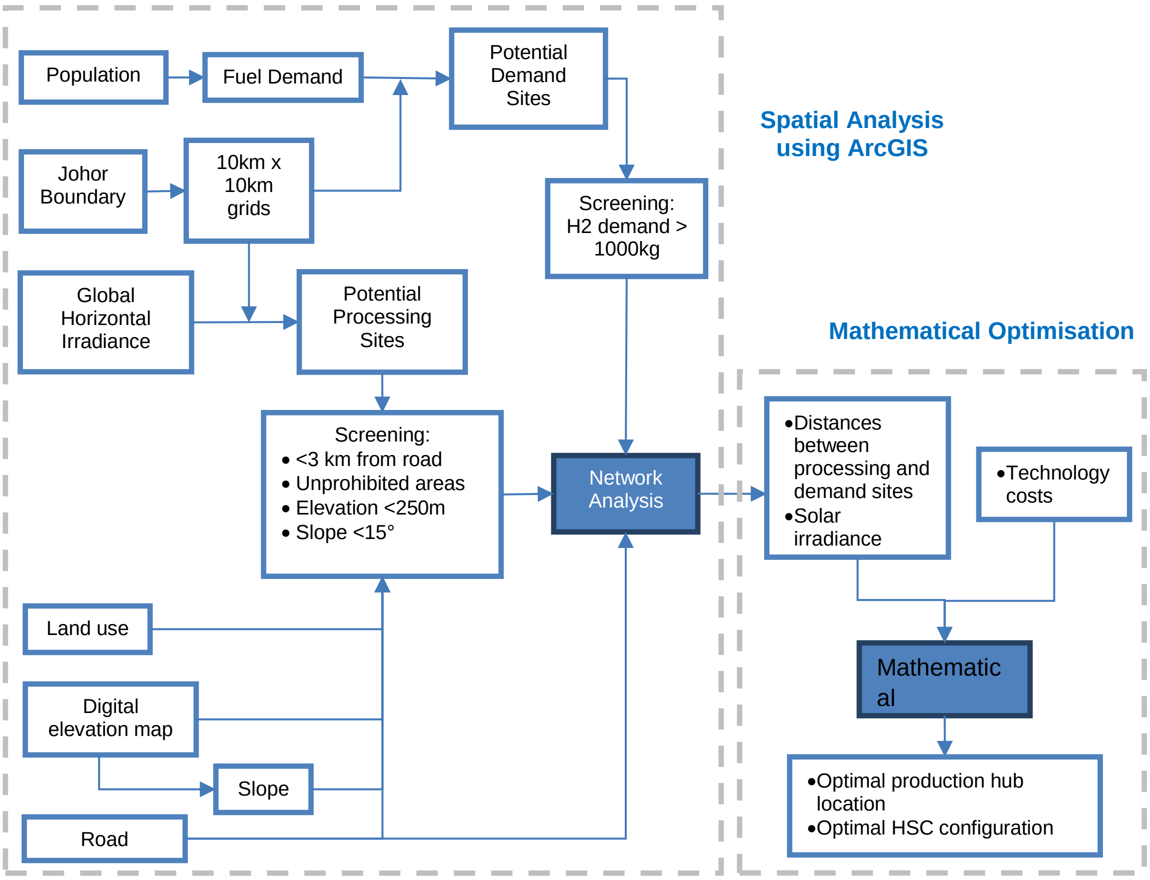

Figure 1: General methodology

2.1 Mathematical Model for Hydrogen Supply Chain

This section discusses the mathematical model for HSC operation, where the model variables are emboldened. Fig. 2 illustrates the overview of hydrogen supply network. The electricity generated by solar panel is converted to hydrogen via electrolyser, which is then stored and transported to the demand site using trucks.

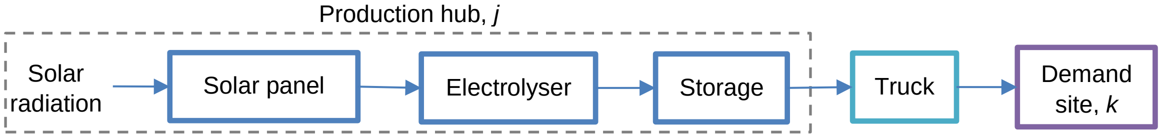

Figure 2: Configuration of Hydrogen Supply Chain

The electricity produced by solar panel in production hub *j*, $\mathbf{E_j^G}$ is given by Eq(1), where $\mathrm{SR_j}$ is the solar radiation at production hub *j*, $\mathbf{A_j^{PV}}$ is the area of solar panel at production hub *j*, $\mathbf{B_j}$ is the binary determinant for the presence of production hub *j*, and $\mathrm{PV^{EFF}}$ is the efficiency of solar panel. Eq(2) computes the amount of hydrogen produced from electricity, $\mathbf{H_j^G}$**,** where $\mathrm{Y^{EL}}$ is the yield of electrolyser. Eq(3) limits the area of PV system subjected to land availability. The capacity of solar panel in terms of kWp can be obtained through Eq(4).

$$\boldsymbol{E_j^G} = SR_j\, \boldsymbol{A_j^{PV}}\, \boldsymbol{B_j}\, PV^{EFF} \quad \forall j \tag{1}$$

$$\boldsymbol{H_j^G} = \boldsymbol{E_j^G}\, Y^{EL} \quad \forall j \tag{2}$$

$$\boldsymbol{A_j^{PV}} \leq A_j^{Land} \quad \forall j \tag{3}$$

$$\boldsymbol{PW_j^{PV}} = \boldsymbol{A_j^{PV}}\ PV^{EFF} \quad \forall j \tag{4}$$

The amount of hydrogen transported from production hub *j* to demand site *k*, $\mathbf{H_{j,k}^T}$ must be less or equal than the hydrogen produced in production hub *j*, as shown in Eq(5). Eq(6) indicates the amount of hydrogen transported to demand site *k* should satisfy the demand, $\mathrm{H_k^D}$.

$$\textstyle\sum_k \boldsymbol{H_{j,k}^T} \leq \boldsymbol{H_j^G} \quad \forall j \tag{5}$$

$$\textstyle\sum_j \boldsymbol{H_{j,k}^T} \geq H_k^D \quad \forall k \tag{6}$$

The equations for truck transportation are adopted from Almansoori and Shah (2006). The number of trips required to transport hydrogen, $\mathbf{N_{j,k}^{trip}}$ is given by Eq(7), where $\mathrm{T^{Cap}}$ is the capacity of truck. The number of trucks, $\mathbf{N_{j,k}^{truck}}$ required can be computed using Eq(8), where $\mathrm{T^{TA}}$ is the time available of the truck in a day. The time required to travel between production hub and demand site, $\mathbf{T_{j,k}^{trip}}$ can be calculated using Eq(9), where $\mathrm{D_{j,k}}$ is the road transportation distance between production and demand sites calculated during the spatial analysis stage, SP is the mean speed of truck, and $\mathrm{T^L}$ is the loading and unloading time.

$$\boldsymbol{N_{j,k}^{trip}} \geq \frac{\boldsymbol{H_{j,k}^T}}{T^{Cap}} \quad \forall j,k \tag{7}$$

$$\boldsymbol{N_{j,k}^{truck}} \geq \frac{\boldsymbol{N_{j,k}^{trip}} T_{j,k}^{trip}}{T^{TA}} \quad \forall j,k \tag{8}$$

$$T_{j,k}^{trip} = \frac{2D_{j,k}}{SP} + T^L \quad \forall j,k \tag{9}$$

The objective function of this model is to minimise the annual cost of HSC that is defined in Eq(10), where CRF is the capital recovery factor. The total facility capital cost is illustrated in Eq(11), where $\mathrm{PV^{capex}}$ is the capital cost of solar panel, $\mathrm{EL^{capex}}$ is the capital cost of electrolyser, and $\mathrm{ST^{capex}}$ is the capital cost of hydrogen storage tank. The transportation capital cost is given in Eq(12), where $\mathrm{T^{capex}}$ is the capital cost of truck. The facility operating cost is shown in Eq(13), where $\mathrm{PV^{opex}}$ is the operating cost of solar panel, $\mathrm{EL^{opex}}$ is the operating cost of electrolyser and $\mathrm{ST^{opex}}$ is the operating cost of storage tank. The transportation operating cost is shown in Eq(14), where FC is the fuel cost, OPD is the number of operating days in a year and $\mathrm{T^{FE}}$ is the fuel economy of truck. Eq(15) shows the formula for capital recovery factor where r is the interest rate and PL is system lifespan.

$$C^{Annual} = CRF\left(C^{FCC} + C^{TCC}\right) + C^{FOC} + C^{TOC} \quad (10)$$

$$C^{FCC} = \sum_j PW_j^{PV}\, PV^{capex} + \sum_j PW_j^{PV}\, EL^{capex} + \sum_j H_j^G\, ST^{capex} \quad (11)$$

$$C^{TCC} = \sum_{j,k} N_{j,k}^{truck}\, T^{capex} \quad (12)$$

$$C^{FOC} = \sum_j PW_j^{PV}\, PV^{opex} + \sum_j PW_j^{PV}\, EL^{opex} + \sum_j H_j^G\, ST^{opex} \quad (13)$$

$$C^{TOC} = \sum_{j,k}\left(2N_{j,k}^{Trip} D_{j,k} \frac{FC}{T^{FE}}\right) OPD \quad (14)$$

$$CRF = \frac{r(1+r)^{PL}}{(1+r)^{PL}-1} \quad (15)$$

3. Result and Discussion

This section discusses the results of spatial analysis and mathematical optimisation. Spatial analysis screens the potential processing sites while mathematical optimisation identifies the optimal processing site location.

3.1 Spatial Analysis

Figure 3a and Figure 3b show the GIS map produced by collecting and processing the spatial data in ArcGIS. Figure 3a presents the spatial average global horizontal irradiance retrieved from Global Solar Atlas (2019). The entire region of study has been divided into 10 km × 10 km grids while the empty areas in the grids are eliminated to illustrate the region more precisely. The location of each grid is represented by the centre point. Geographical factors such as land-use, elevation, slope, and distance to the nearest road are used to screen out the infeasible areas for production sites, and the feasible production sites are as shown in Fig. 3a. Fig. 3b shows the hydrogen demand in each grid, where the grids with high hydrogen demand (>1,000 kg/d) are indicated with red markers. This work considers an introductory phase of hydrogen economy and the modelled HSC is expected to fulfil 20 % of the vehicle fuel demand at populated regions. The spatial distribution of the population is used to estimate the vehicle fuel demand in each grid and the grids with hydrogen fuel demand over 1,000 kg have been selected as the demand sites. The daily fuel demand of each grid is calculated through Eq(16), where $\mathrm{Pop_k}$ is the population in each grid, $\mathrm{Pop^{Total}}$ is the total population in Johor, $\mathrm{Vehicle^{Total}}$ is the total number of vehicles in Johor, VKT is the average distance travelled annually by the vehicles in Johor, and $\mathrm{V^{FE}}$ is the fuel economy of fuel cell electric vehicles. The spatial population in Malaysia can be obtained from WorldPop (2013). Through spatial analysis, 119 potential production sites and 16 demand sites have been identified. The distance between potential production sites and the demand sites is computed and used in the mathematical optimisation model.

$$H_k^D = \frac{Pop_k}{Pop^{Total}} \frac{VKT}{365}\, Vehicle^{Total}\, V^{FE} \quad \forall k \quad (16)$$

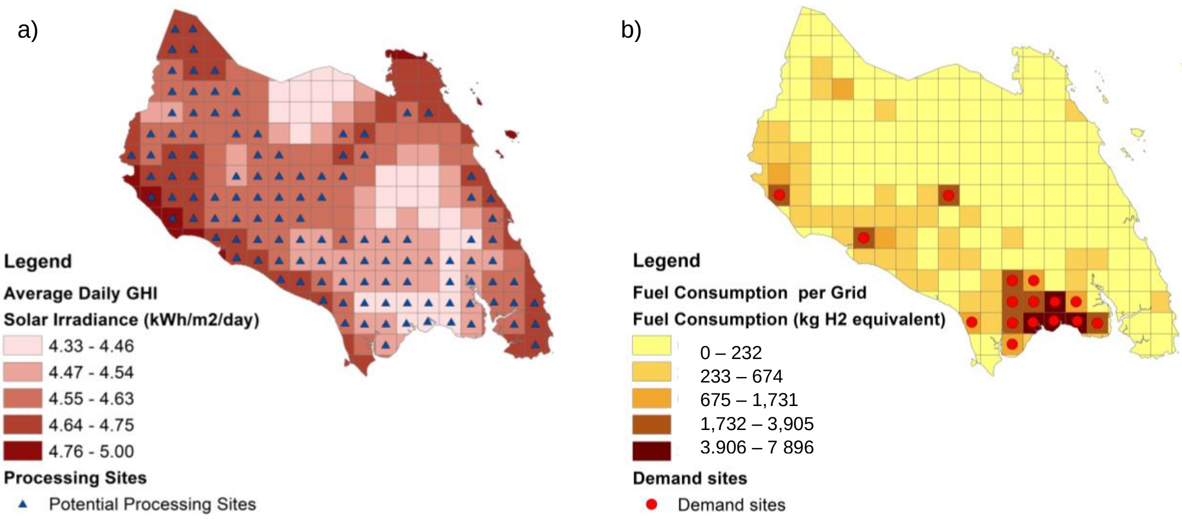

Figure 3: (a) Average global horizontal irradiance in each grid (b) Hydrogen demand in each grid

3.2 Mathematical Optimisation

For this study, the number of production site is set to be 1 to identify the most suitable location for hydrogen production through mathematical optimisation. The mixed-integer linear programming (MILP) model developed contains 1,951 continuous variables, 3,104 integer variables, and 97 binary variables. Commercial optimisation software GAMS, in HP Probook 440 G6 with Intel Core i5-8265U (1.60 GHz) processor and 8 GB RAM is used to solve the MILP model. The average Central Processing Unit (CPU) time for the generation of solution is 0.16 s with zero optimality gap. Table 1 shows the parameters used for the case study which includes the costing information and their references. The HSC is expected to last for 20 years and operate every day with 5 % interest rate for the initial investment. The truck transportation is assumed to work 12 h per day, with 60 km/h mean driving speed and 2 h loading and unloading time. Since the cost of diesel is highly variable, an average cost 0.55 USD/L is taken for the case of Malaysia, yet it should be noted that the fluctuation in fuel cost would affect the cost of transportation, as well as the optimal location of production site.

Table 1: Parameters used in mathematical optimisation

Parameter	Value	Unit	Ref
Network operating period	365	d	
Plant lifetime	20	yr	
Interest rate	5	%	
Efficiency of solar panel	15.8	%	(Maleki, 2018)
Capital cost of solar panel	1806	USD/kWp	(Maleki, 2018)
Operating and maintenance cost of solar panel	54	USD/kWp/y	(Maleki, 2018)
Yield of electrolyser	0.021	kg H_2/kWh	(Reuß et al., 2017)
Capital cost of electrolyser	550	USD/kW	(Reuß et al., 2017)
Operating and maintenance cost of electrolyser	16.5	USD/kW/y	(Reuß et al., 2017)
Storage capital cost	555	USD/kg	(Reuß et al., 2017)
Storage operating and maintenance cost	11.1	USD/kg/y	(Reuß et al., 2017)
Truck capacity	670	kg	(Reuß et al., 2017)
Truck capital cost	605,000	USD	(Reuß et al., 2017)
Truck available time	12	h/d	
Truck mean speed	60	km/h	
Truck fuel economy	2.55	km/L	(Almaraz et al., 2013)
Loading and unloading time	2	h	
Fuel cost	0.55	USD/l	(RinggitPlus, 2020)

The optimal location to construct a hydrogen production hub is illustrated in Figure 4a. The annual cost of HSC operation is determined as 159.3 million USD and a 583 MWp PV system is required for the given hydrogen demand. It can be observed that the selected location has a relatively high solar irradiance and is situated in between 3 demand sites. The fact that the selected production site is not close to the regions with high hydrogen demand suggests the capacity of PV system has a greater impact to the total cost of the system as compared to the transportation distance. This is supported by the cost breakdown in Figure 4b, where the cost of PV system is much significant than the transportation cost. Although the selected site has longer transportation distance to the demand locations, it receives higher solar irradiance which reduces the cost of PV system.

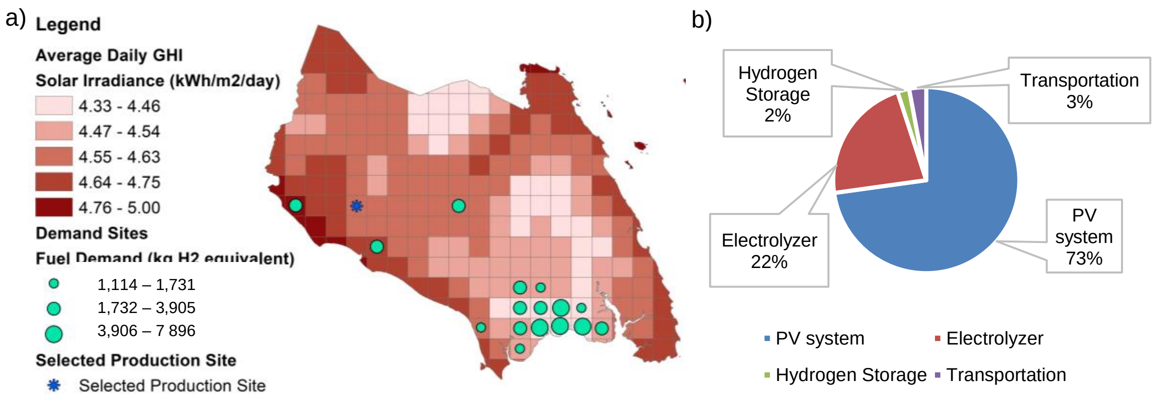

Figure 4: (a) Final selected processing site (b) Breakdown of HSC annual cost

4. Conclusions

This study proposed an integrated GIS-mathematical optimisation framework for solar-based hydrogen supply chain modelling. Geographical factors such as land-use, transportation network, and solar irradiance are used to screen suitable sites for hydrogen production. Through spatial analysis, 119 potential production sites and 16 demand sites have been identified. The optimal production site location has been determined for Johor, Malaysia with an annual cost of 159.3 million USD. The optimisation outcome suggests that the capacity of PV system has a greater influence on the system cost as the selected site is at a region with higher solar radiation instead of a region with shorter transportation distance to the demand sites. This study provides a holistic framework that includes geographical considerations and site selection when optimising the hydrogen supply chain. Future study should consider a more comprehensive hydrogen supply chain network with more options for hydrogen production, storage, transportation and application. Attention should also be drawn to the temporal variability of energy sources.

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