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Energy Trading of Renewable Energy from Malaysia to Singapore

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Sustainable energy planning and development are necessary to move towards net zero emissions. Cross-border electricity trading and green hydrogen trading are sustainable options to increase renewable energy capacity growth. Using the solar energy potential in Peninsular Malaysia, the hydropower potential in East Malaysia as an energy supply source, and the electricity demand of Singapore as the demand side, this study aimed to reveal the potential electricity and hydrogen trading activities within these two countries. A mixed integer non-linear programming mathematical model with an objective function to minimize the overall cost was developed using the General Algebraic Modeling System. The results shows that hydropower-generated electricity from East Malaysia is most cost-effective in satisfying Singapore's electricity demand, with a total cost of 1.15×10^{11} USD, resulting in an LCOE of 0.1203 USD/kWh. The deployment of a new hydropower plant capacity was found to be 6.54 GW, with annual electricity production of 36.6 TWh to satisfy the electricity demand of Singapore. This study also found that energy trading in the form of electricity transmission via submarine power cable from East Malaysia results in the lowest cost, followed by electricity transmission via power cable from Johor, and hydrogen pipeline transportation from Johor. Hydrogen shipping from East Malaysia is infeasible due to limited hydropower resource available. The model developed from this study can provide insight for policymakers, investors, and developers in the early stages of project development.

1. Introduction

The issue of global warming was announced in the past three decades, but the condition has worsened over time. Most countries signed nationally determined contributions in the Paris Agreement to support reducing greenhouse gas emissions. Electricity drives economic growth and rapid development, but electricity production heavily relies on fossil fuels. Fossil fuels lead to global warming, and they are not a secure energy source, as they will be depleted one day.

Renewable energy is a green and sustainable source that can replace the role of fossil fuels in energy generation. The availability of renewable energy highly depends on the geographical location. Bilateral energy trading between countries with surplus solar and wind energy availability to the nearby countries could be the stepping stone for ASEAN to be more prepared for future grand sustainable planning (Do and Burke, 2023). Jha et al. (2022) concluded that electricity transmission from one entity to another encourages the development of renewable energy in energy generation (Jha et al., 2022). Singapore decided to import 4 GW of renewable energy by 2035 to increase renewable energy (Energy Market Authority of Singapore, 2022).

Chattopadhyay et al. (2020) studied a bi-directional cross-border electricity trading study between India-Bangladesh, India-Bhutan, India-Nepal, and India-Sri Lanka. An Electricity Planning Model (EPM) that can inspect the economic viability and projection of the new power plant expansion to cater to future planning was developed (Chattopadhyay et al., 2020). Chen et al. (2020) used the General Algebraic Modeling System (GAMS) language to develop a model to supply heat and electricity to the demand side (Chen et al., 2020). Regional-based economic analysis was done on integrated mixed energy resources, including renewable energy and fossil fuels, as energy supply sources in Northwestern Europe. The study shows that regional cost is one of the obstacles to promoting the power exchange between the involved parties. Mertens et al. (2020)

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conducted a study to compare the impact of neglecting cross-border trade versus endogenously integrating all neighbouring countries for an investment planning model for the Central-Western European power system (Mertens et al., 2020). The study results showed that endogenizing the dispatch decisions was the most accurate way to address cross-border trading, but the downside was longer computational time.
Besides cross-border electricity transmission, energy can be stored and traded as H_2. Schlund (2023) developed a mixed-integer linear programming model to perform cross-border H_2 trading by repurposing natural gas pipelines in European regions (Schlund, 2023). The cost-efficient results provide strategic planning for the H_2 network in Europe.
The research showed that energy trading from one region to another is a good alternative to moving towards the era of sustainable energy generation. Mathematical modelling is a great tool for revealing the feasibility of the study in terms of economic and technical viability. This study develops a mixed-integer non-linear programming (MINLP) mathematical model using the GAMS platform to minimize the total cost while satisfying the electricity import target of Singapore from the neighbouring country, Malaysia.

2. Methodology

A mathematical model with the objective function of minimizing the total cost of the study will be developed via GAMS. The total cost is made up of 10 expenses, including CAPEX and OPEX for three main equipment (solar plant, hydropower plant and electrolyzer), cost of power cable, cost of H_2 transmission via pipeline, cost of submarine power cable, and H_2 shipping cost. The cost of equipment CAPEX, CEqpCapex(t), USD/y is calculated as in Eq(1), where NewEqpSize(t) is the deployment of new equipment capacity (with unit of kWp for solar plant, kW for hydropower and electrolyzer), EqpCapexUP(t) is the equipment CAPEX unit price (with unit of USD/kWp for solar, USD/kW for hydropower and electrolyzer), AF is amortization factor (with interest rate of 5 % and lifespan of solar (Energy Efficiency & Renewable Energy, 2024), hydropower (Indiana Office of Energy Development, 2024) and electrolyzer (Mah et al., 2021) were assumed to be 30, 100, and 8 y), and Op(t) is the operating period, y, from present year until the end of study period, 2050. The cost of equipment OPEX, CEqpOpex(t), USD/y, is calculated via Eq(2), where EqpCapacity(t) is the capacity of equipment, kW, and EqpOpexUP(t) is the OPEX unit price of equipment, USD/kW/y. The CAPEX and OPEX unit price for the equipment are listed in Table 1. It is assumed that the annual unit price for electrolyzer and hydropower plant depreciates less than 3 %, and solar plant depreciate less than 10 %.

$$\text{CEqpCapex}(t) = \text{NewEqpCapacity}(t) \times \text{EqpCapexUP}(t) \times \text{AF} \times \text{Op}(t) \quad \forall\ \text{Eqp} = \text{solar plant, hydropower plant, and electrolyzer} \tag{1}$$

$$\text{CEqpOpex}(t) = \text{EqpCapacity}(t) \times \text{EqpOpexUP}(t) \quad \forall\ \text{Eqp} = \text{solar plant, hydropower plant, and electrolyzer} \tag{2}$$

Table 1: Equipment CAPEX and OPEX unit cost from 2025 to 2050

Equipment	CAPEX	OPEX
Solar Power Plant	851.06 to 368.83 USD/kWp (Weng, 2024)	24.68 to 17.35 USD/kW/y (National Renewable Energy Laboratory, 2023b)
Hydropower Plant	3,008 to 2,598 USD/kW (National Renewable Energy Laboratory, 2023a)	85 to 74 USD/kW/y (National Renewable Energy Laboratory, 2023a)
Electrolyzer	1,075 to 634 USD/kW (Navarrete and Zhou, 2024)	21.5 to 12.7 USD/kW/y (Mah et al., 2021)

Eq(3) and Eq(4) calculated cost of land (CLandCable, USD) and sea cable(CSeaCable, USD), where Dist(L) is the distance from Peninsular Malaysia (1.9 km) and East Malaysia (1070 km) to Singapore. AF40 and AF20 represent the amortisation factor of 5 % interest rate, 40 y lifespan for land (Xcel Energy Inc., 2014) and 20 y lifespan for sea power cable (TeleGeography, 2024). B1(t) is the binary variable links Eq(3) with Eq(8), where the CLandCable(t) will be calculated if and only if the power cable was used to satisfy the demand. Similarly, B2(t) is the binary variable links Eq(4) with Eq(17).
The cost of addition of H_2 pipeline transportation, CH_2Pipeline(t) was calculated as in Eq(5), where H_2Land(t), is the quantity of H_2 for pipeline transportation, PipelineUP is the unit price of H_2 pipeline transportation, 0.002 USD/km, AF50 is amortization factor of 5 % interest rate with 50 y lifespan. Eq(6) is to calculate the cost of H_2 shipping from East Malaysia to Singapore, CH_2Shipping, USD, where H_2Sea(t) is the H_2 produced for shipping purposes, ShippingUP is the shipping unit cost of H_2, 2.25 USD/kg H_2/km.

$$\text{CLandCable}(t) \geq \text{Dist}(L) \times \text{CableUP} \times \text{AF40} \times \text{Op}(t) \times \text{B1}(t) \tag{3}$$

$$\text{CSeaCable}(t) = \text{Dist}(L) \times \text{SeaCableUP} \times \text{AF20} \times \text{Op}(t) \times \text{B2}(t) \tag{4}$$

$$CH_2Pipeline(t) = H_2Land(t) \times Dist(L) \times PipelineUP \quad (5)$$

$$CH_2Shipping(t) = H_2Sea(t) \times ShippingUP \times Dist(t) \quad (6)$$

Table 2: Energy trading mode and infrastructure unit price

Energy Trading Mode and Cost	Peninsular Malaysia	East Malaysia
H_2 Transportation	Pipeline (Cost: 2 USD/kg H_2/km)	Shipping (Cost: 2.25 USD/kg H_2/km)
Power Transmission	Power Cable (1.243 × 10^6 USD/km)	Submarine Power Cable (2.5 × 10^6 USD/km)

Eq(7) is the energy balance equation at the demand side, where the electricity demand of Singapore, ED(t) equals to the sum of electricity generated from solar, SolarElec(t), kWh, electricity generated from hydropower, HydroElec(t), kWh, equivalent energy transferred via pipeline (H_2LandElec(t), kWh) and shipping (H_2SeaElec(t), kWh), with the consideration of electricity transmission loss, ELoss(c), 0.007 % losses per km for land power cable, and 0.004 % losses per km for the submarine power cable. Electricity generated from solar, SolarElec(t), kWh/y was calculated as in Eq(8), where SolarIrr is solar irradiance in Johor state of Peninsular Malaysia, with annual irradiance of 1607.6 kWh/m^2/y, SolarA(t) is the size of the solar panel for electricity generation, m^2, and SEff is the solar plant efficiency, that is 21.5 %.

$$ED(t) = SolarElec(t) – SolarElec(t) \times ELoss(C) \times Dist(L) + HydroElec(t) – HydroElec(t) \times ELoss(C) + H_2LandElec + H_2SeaElec \quad (7)$$

$$SolarElec(t) = SolarIrr \times SolarA(t) \times SEff \times B1(t) \quad (8)$$

H_2 production for pipeline transportation, H_2Land(t) is calculated using Eq(9), where SolarB(t) is the size of solar panel for H_2 generation, m^2, and EltEff is electrolyzer conversion coefficient, 0.0195 kg H_2/kWh. H_2 production for shipping transmission, H_2Sea(t) is calculated via Eq(10), where HydroCapB(t), kW, is hydropower plant capacity for H_2 generation, HCF is the capacity factor of hydropower, 71 % (Soong and Yoong, 2022), HydroEff is hydropower plant efficiency, 90 %, and HydroOp(t) is total hour per year, 8,760 h. Eq(11) and Eq(12) are electricity generation from H_2 transported via pipeline and shipping, where FCEff is fuel cell efficiency, 55 %, and H_2 Energy is the calorific value of H_2, that is 33.33 kWh/kg H_2 in this study. Eq(13) and Eq(14) are used to calculate the electrolyzer capacity for H_2 pipeline in Peninsular Malaysia, EltSizeA(t), and electrolyzer capacity for H_2 shipping from East Malaysia to Singapore, EltSizeB(t), where EltOp(t) is electrolyzer annual operating hour, 8,760 h.

$$H_2Land(t) = SolarIrr \times SolarB(t) \times SEff \times EltEff \quad (9)$$

$$H_2Sea(t) \leq HydroCapB(t) \times HCF \times HydroEff \times HydroOp(t) \times EltEff \quad (10)$$

$$H_2LandElec(t) = H_2Land(t) \times FCEff \times H_2Energy \quad (11)$$

$$H_2SeaElec(t) = H_2Sea(t) \times FCEff \times H_2Energy \quad (12)$$

$$EltSizeA(t) \times EltOp(t) = H_2Land(t) \quad (13)$$

$$EltSizeB(t) \times EltOp(t) = H_2Sea(t) \quad (14)$$

Eq(15) calculates the hydropower plant capacity, HydroCap(t), where HydroResource(t) is the hydropower potential found in East Malaysia, 893.52 TWh/y. Eq(16) splits the hydropower plant capacity for two different purposes, one for electricity generation, HydroCapA(t), kW, and the other one for H_2 generation, HydroCapB(t), kW. Eq(17) calculates the electricity generation from the hydropower plant, HydroElec(t), and the electricity will be transmitted to Singapore via submarine sea cable. Eq(18) calculates the new plant for solar and hydropower, NewRE_n, kW, where RE can be replaced by solar and hydropower technology, and n can be replaced by abbreviation A, and B, where A represents electricity generation and B represents H_2 generation purpose, ExRE_n(t) represents existing plant, kW, which the capacity was assumed as 0 in this study.

$$HydroResource(t) \geq HydroCap(t) \times HCF \times HydroOp(t) \quad (15)$$

$$HydroCap(t) = HydroCapA(t) + HydroCapB(t) \quad (16)$$

$$HydroElec(t) = HydroCapA(t) \times HCF \times HydroEff \times HydroOp(t) \times B2(t) \quad (17)$$

$$NewRE\_n(t)+ExRE\_n(t)-ExRE\_n(t-1) = RE\_n(t)-RE\_n(t-1)\ \forall\ RE = solar, hydropower;\ n= A, B \quad (18)$$

3. Case Study

In this study, the electricity demand of Singapore was fixed at 4GW throughout the study period, from 2025 to 2050 (Energy Market Authority of Singapore, 2022). Malaysia planned to use the remaining capacity of the existing power line connecting Malaysia-Singapore, and the maximum electricity traded would be capped at 300 MW (Aziz, 2024). Any extra electricity traded from Peninsular Malaysia to Singapore will be required to install power transmission cable. The renewable energy sources for Peninsular Malaysia will be solar energy, and East Malaysia will generate electricity from hydropower. The solar irradiance for Peninsular Malaysia is 1607.6 kWh/m^2 in Johor (The World Bank Group, 2024), and 10.2 GW of hydropower potential in East Malaysia (SEDA Malaysia, 2021). If electricity trading is insufficient to satisfy the power demand of Singapore, the deficit can be met by energy in the form of H_2, via H_2 pipeline or H_2 shipping. The related cost for equipment and energy trading was depicted as in Table 1 and Table 2.

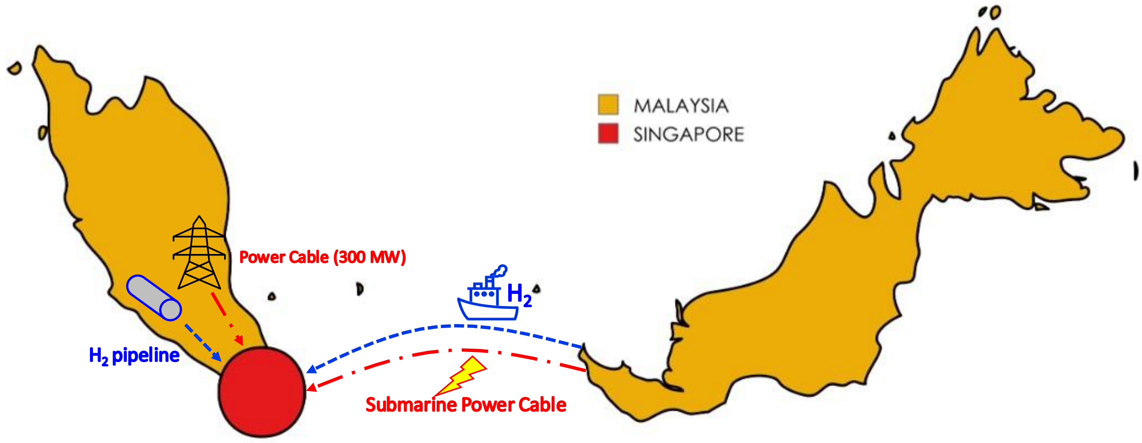

Figure 1: Illustrative diagram of the case study

4. Results and Discussions

4.1 Case study results

The average LCOE of the study was 0.1203 USD/kWh, and total cost throughout the study was 1.15×10^{11} USD, where first year of the study required 3.19×10^{10} USD of expenses, mainly made up of new hydropower plant cost, CEcapex, 2.58×10^{10} USD and submarine cable, CSeaCable, 5.58×10^{9} USD deployment cost in Peninsular Malaysia. The results showed that all the electricity imported by Singapore will be originated from hydropower energy from East Malaysia. The reason renewable energy resource from East Malaysia was selected instead of that of Peninsular Malaysia is due to the efficiency and capacity factor of hydropower plant higher than that of solar plant. For East Malaysia, there are two options to satisfy the electricity demand of Singapore, either in the form of electricity transmission through the submarine power cable and/or converting the hydropower electricity into H_2 and transporting via H_2 shipping. In this study, the model decided to deploy 6.54 GW of new hydropower plant, transfer electricity through 1,070 km submarine cable to Singapore. The annual electricity transferred from East Malaysia to Singapore is 36.61 TWh, where 1.57 TWh of electricity was lost due to submarine cable resistance over the long transmission distance.

The utilization of the remaining 300 MW capacity of the existing power cable connecting Peninsular Malaysia-Singapore is not being prioritized because the overall cost of the study would be 14 % higher than the optimized results. The capacity of hydropower plant reduced from 6.54 GW to 6.05 GW, the energy supply gap was compensated with the deployment of 9.55 GW solar PV plant. When the priority of energy trading was given to the remaining capacity of the existing power cable, Singapore still required to import 33.9 TWh of electricity via submarine cable from East Malysia. The CAPEX cost for new hydropower plant reduced from 2.58×10^{10} USD to 2.38×10^{10} USD, but an additional CAPEX cost of 1.38×10^{10} USD for solar PV makes this decision not favorable.

4.2 Sensitivity analysis

In the case study of Section 4.1, the model is free to select any method to satisfy the electricity demand of Singapore. The options to meet electricity demands comprised of (a) solar-generated electricity transmission from Peninsular Malaysia via power cable, (b) solar-based H_2 transportation via a pipeline system from Peninsular Malaysia, (c) hydropower-generated electricity transmission from East Malaysia via submarine power cable, and (d) hydropower-based H_2 shipping from East Malaysia to Singapore.

This section determines each option's priority in satisfying electricity demand. For each analysis, the model will be rerun with fewer options each time, eliminating the method being prioritized in the previous run.

In Analysis 1, (c) hydropower-generated electricity transmission from East Malaysia via submarine power cable was excluded from the model as the option was being prioritized in the case study in Section 4.1. Analysis 1 showed that without option (c), the model decided to satisfy the demand by converting all the solar energy into electricity and transmit to Singapore via land power cable. The total cost for this solution doubled than that of the optimized solution, 2.48×10^{11} USD, where the deployment of new solar plant with capacity of 127.35 GW costs 1.83×10^{11} USD. For Analysis 2, as the solar-generated electricity was given priority to satisfy the demand, option (a) was excluded. The model would prefer to satisfy the electricity demand of Singapore using solar-based H_2 transportation via a pipeline system from Peninsular Malaysia, with total costs of 6.94×10^{11} USD. The model decided to deploy 356 GW of new solar plant, convert all the harvested solar electricity to H_2 using 218 MW electrolyzer. An annual H_2 production rate of 1.91×10^9 kg H_2/y from Peninsular Malaysia was required to satisfy the electricity demand of Singapore. The H_2 was transferred to Singapore via H_2 pipeline, where the annual cost of transporting H_2 from Peninsular Malaysia to Singapore is 7.26×10^6 USD. For Analysis 3, when the only option to satisfy Singapore's electricity demand is shipping the hydropower-generated H_2 from East Malaysia to Singapore, the model unable to satisfy the Singapore demand. This is due to the huge conversion losses during the process of converting harvested hydropower electricity into H_2, and then convert back to electricity when arrived in Singapore. The limited 10.2 GW of hydropower resources in East Malaysia will produce only 20.4 TWh/y of effective electricity when reaching Singapore, which is insufficient to satisfy the 35 TWh/y of electricity demand.

Table 3: Expenses comparison of case study with analysis 1, 2, and 3

Expenses (USD)	Case study	Analysis 1	Analysis 2	Analysis 3
Solar CAPEX	-	1.83×10^{11}	5.13×10^{11}	Infeasible
Solar OPEX	-	6.42×10^{10}	1.80×10^{11}	Infeasible
Hydropower CAPEX	2.58×10^{10}	-	-	Infeasible
Hydropower OPEX	1.34×10^{10}	-	-	Infeasible
Electrolyzer CAPEX	-	-	1.69×10^{9}	Infeasible
Electrolyzer OPEX	-	-	2.18×10^{8}	Infeasible
H_2 Pipeline Transportation Cost	-	-	1.89×10^{8}	Infeasible
Submarine Sea Cable Transmission Cost	7.53×10^{10}	-	-	Infeasible
Total Cost	1.15×10^{11}	2.48×10^{11}	6.94×10^{11}	Infeasible

5. Conclusion

A MINLP mathematical model optimizing the total cost of a system that satisfies Singapore's electricity demand was developed. The model preferred to trade the energy from Malaysia in the form of electricity rather than converting into H_2 as energy carrier due to huge conversion losses. To meet Singapore's annual 35.04 TWh electricity demand, 36.61 TWh hydropower energy from East Malaysia was harvested and transmitted via submarine power cable to Singapore. This option resulted in the lowest total cost, 1.15×10^{11} USD.

A series of sensitivity analyses revealed the priority of the options to satisfy Singapore's electricity demand. The results showed that electricity transmission via submarine sea cable is the best option, followed by electricity transmission via power cable, and H_2 pipeline transportation. H_2 shipping is the least efficient method in this study due to long shipping distances, and energy losses during the resource conversion processes. The findings from this study can provide valuable advice for policymakers, governments and developers. In future, the model can be extended to include more countries, renewable energy and modes of transport to represent more realistic scenarios.

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