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Levelized Cost of Green Hydrogen Production in the Philippines

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As climate change is slowly materialising, the importance of alternative fuels has been magnified to aid in reducing carbon emissions. One of the most promising clean alternative fuels is green hydrogen which is produced via water electrolysis powered by renewable energy sources. The solar and wind power potential of the Philippines has been explored in published studies; however, the economic viability of green hydrogen production has not yet been evaluated. In this work, an assessment of the levelized cost of hydrogen (LCOH) produced from solar and wind power in the Philippines was performed. Representative locations within a province were selected based on the annual average resource availability for solar global horizontal irradiance (GHI) and wind speed. LCOH calculations identified the favourable locations for green H_2 production by calculating the net present cost (NPC) of solar- and wind-powered electrolysis plants with deionised water as feedstock. Uncertainty analysis was performed via Monte Carlo simulations by perturbing component costs, feedstock water price, and discount rate. Additionally, LCOH calculations and Monte Carlo simulations showed the disparity of resource availability between solar and wind in the Philippines – supported by the calculated capacity factors. It was also shown that favourable conditions such as high solar GHI and high wind speed tend to have a narrower distribution and lower LCOH values – implying less economic risks in developing over these locations. Calculations identified that policy instruments such as subsidies and tax exemptions are still vital in commissioning green hydrogen plants, as LCOH values are generally higher than the cost of grey hydrogen.

1. Introduction

Reduction of carbon emissions is a worldwide effort to combat climate change. With this as a main objective, the Paris Agreement intends to decrease the role of fossil fuels in the global energy mix and aims for cleaner energy sources. The Philippines is one of the signatories to the Paris Agreement – promising to reduce carbon emissions to 75 % from 2017 to 2030 (Dela Cruz and Davies, 2021). Three-quarters of the current Philippine energy mix is still fossil fuel-based, while the remaining quarter is from renewable energy such as hydro, geothermal, solar, and wind (International Trade Administration, 2020). In 2020, the transportation and industrial sectors were responsible for 39 % of the CO_2 emissions in the Philippines, while the largest contributor is the power sector, with 51 % contribution (Climate Transparency, 2020). Renewable energy (RE) power plants can reduce emissions in the power sector. However, transitioning the industrial and transportation sectors to clean energy is more challenging since an energy vector is required to deliver clean energy to the necessary locations. Hydrogen is considered a clean energy vector and fuel because it only produces water during energy generation. The emissions associated with hydrogen primarily arise from its production process, with steam methane reforming (SMR) being the most economically viable method. To mitigate emissions from hydrogen production, various methods have been developed, resulting in different types of hydrogen, such as grey hydrogen (from SMR), blue hydrogen (from SMR with carbon capture), and green hydrogen (from water electrolysis using RE) (Ajanovic et al., 2022). Of these types, green hydrogen is undoubtedly the cleanest as it is produced purely from RE sources such as solar and wind. The biggest barrier to green hydrogen uptake is cost as production

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processes are still relatively expensive, but green hydrogen use is likely to rise as renewable energy is constantly getting cheaper (Eh et al., 2022).

To evaluate the economic feasibility of green hydrogen production systems, techno-economic investigations estimate the levelized cost of hydrogen (LCOH). This entails calculating the expenses of producing one kilogram of hydrogen from renewable sources using electrolysers coupled with an RE source. Rezaei et al. (2019) investigated the economic viability of a wind turbine-electrolyser system for hydrogen production in Afghanistan without any energy storage component. In their study, LCOH was calculated directly from the LCOE of wind power generation for all 34 capital cities of Afghanistan. Benalcazar and Komorovska (2022) assessed the LCOH production from solar and wind sources in the NUTS-2 regions of Poland and generated a heatmap of the LCOH to illustrate the spatial distribution of LCOH. In addition, Monte Carlo-based simulations were performed to investigate the uncertainties tied to varying costs of equipment, cost of electricity, discount rate, and the price of water. Monte Carlo simulations have also been used to compare the efficiency of different electrolyser technologies such as alkaline water electrolyser (AWE), proton exchange membrane electrolyser (PEMEC), solid oxide electrolyser (SOEC), and SOEC with waste heat recovery (SOEC-WH) (Jang et al., 2022).

There is a promise for renewable energy systems in the Philippines, as several studies have found that a certain level of RE penetration in current energy systems will reduce the cost of electricity. Ocon and Bertheau (2019) found that the transition from purely diesel-based systems to solar photovoltaics (solar PV)-battery-diesel systems can induce an average drop in the levelized cost of electricity (LCOE) by around 20 % for off-grid islands. Gulagi et al. (2021) detail a transition pathway towards 100 % renewable energy dependence in the power, heat, transport, and desalination in the Philippines in which they discussed the role of hydrogen and hydrogen-based synthetic fuels in the transportation sector and suggested a possibility of independence from fossil fuels by 2050.

While there is an abundance of studies tackling the RE potential of the Philippines, the conversion of RE to hydrogen fuel via electrolysis is not yet explored for the Philippines. To address this lack of knowledge about the LCOH of green hydrogen in the Philippines, techno-economic assumptions were used in this work to calculate the LCOH of solar- and wind-powered electrolysis plants. The LCOH was then evaluated for the Administrative Level 2 divisions or provinces of the Philippines both for solar PV- and wind turbine-electrolyser systems. In addition, uncertainty analysis was done via Monte Carlo simulations in selected provinces based on calculated LCOH. This work serves as an initial investigation of the feasibility of solar- and wind-powered green hydrogen plants in the Philippines by evaluating the LCOH and by narrowing down the locations where green hydrogen plants can be established.

2. Methodology

The methods used in this work are detailed in this section. LCOH was evaluated using the system architecture presented in Section 2.1 and geospatial data discussed in Section 2.2. LCOH for all Philippine provinces were calculated, and uncertainty analysis was performed for the locations with the lowest, median, and highest LCOH for both solar- and wind-powered systems.

2.1 System architecture

The system used in this work is simplified to a solar PV or wind turbine connected to an electrolyser, shown in Figure 1. Electricity is generated by solar PV or by the wind turbine. The produced electricity is then fed to the electrolyzer along with deionised water as the feedstock. This process should produce hydrogen gas with oxygen gas as a by-product which is not of interest in this study. Four types of electrolysers were explored in this study which are AWE, PEMEC, SOEC, and SOEC-WH.

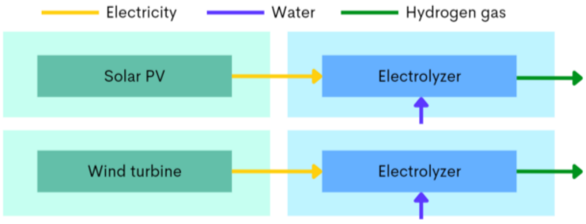

Figure 1: System architecture of the electrolysis plant considered in this work

2.2 Resource data and data selection

Monthly solar global horizontal irradiance (GHI) and wind speed data, with 5-km resolution, were collected from Blanco et al. (2015) and were extracted using QGIS software (QGIS Geographic Information System, 2022). It is not practical to perform a calculation for every point in the dataset, so only locations with the highest annual average resource value for solar GHI and wind speed were selected for each province such that the LCOH calculations were only performed on the best-case scenario for solar PV- and wind turbine-powered systems. A shapefile for the provincial divisions of the Philippines was sourced online (PSA and NAMRIA, 2015) and was utilised to ensure correct selection of data for each province.

2.3 LCOH calculation

LCOH was calculated using a Python-based, in-house microgrid optimisation software, Island System LCOE$_{min}$ Algorithm (ISLA), which was employed by Castro et al. (2020) to perform techno-economic comparisons between different desalination technologies. Techno-economic assumptions shown in Table 1 were inputs in ISLA, along with the resource data for a location, to calculate the net present cost (NPC) and power outputs of solar PV and wind turbine, whose behaviours were taken from Trina Solar (2015) and Wind-turbine-models (2015). The power output dictates the amount in kg of H_2 produced by setting a fixed energy-to-H_2 conversion rate in kWh/kg H_2 taken from Jang et al. (2022). The consumption of water was assumed to be in stoichiometric proportion to the amount of produced H_2.

$$LCOH = \frac{NPC + \sum_{n=1}^{20} C_{H_2O}\left(\frac{1}{1+d}\right)^n}{\sum_{n=1}^{20} W_{H_2}\left(\frac{1}{1+d}\right)^n} \tag{1}$$

Considering a discount rate of 8 % and the cost of water, C_{H2O}, of 0.72 USD/m^3, the LCOH can be calculated using Eq(1) which yields the LCOH in USD/kg. In these systems, the electrolysers were assumed to be producing H_2 whenever power is generated. Two LCOH values per province were calculated for each electrolyser type – one for solar PV-electrolyser system and one for wind turbine-electrolyser system.

Table 1: Techno-economic assumptions used in this work

Component	Basis Capacity	CapEx (USD/kW)	OpEx (USD/kW-y)	Lifetime	Remarks	Ref.
Solar PV: Trina Solar TSM-PC14	310 W	1,935.48	1 % of CapEx	20	Derating Factor: 80 % NOCT: 44 °C Temp. coeff. of P: - 0.41 %/C°	(Feldman et al., 2022)
Wind turbine: Vestas V129-3.0	3 MW	1,000	2.5 % of CapEx	20	Hub height: 119 m Power curve was integrated into the computations.	(US DoE, 2022)
Electrolyzer	1 kW	AWE: 743.87 PEMEC: 793.16 SOEC: 938.87 SOEC-WH: 934.39	AWE: 59.37 PEMEC: 60.37 SOEC: 64.74 SOEC-WH: 64.60	20	Costs are fixed system costs. Energy efficiency is constant, taken from Jang et al. (2022).	(Jang et al., 2022)

2.4 Uncertainty analysis

Table 2: Parameters used for the Monte Carlo simulations

Variable	Distribution	Distribution parameters	Ref.
Solar PV CapEx	Lognormal	Mode = 1,935.48 USD/kW Range = 1,129.03 – 3,870.98 USD/kW σ = 0.292 μ = 5.65	(Heck et al., 2016)
Wind Turbine CapEx	Normal	Mean = 1,000 USD/kW Range = 650 – 1,350 USD/kW σ = 70	(Benalcazar and Komorowska, 2022)
Electrolyzer CapEx and OpEx (values are based on type)	Normal	Mean = values in LCOH calculations Range = within 20 % of the mean σ = 5 % of mean	(Benalcazar and Komorowska, 2022)
Price of water	Triangular	Peak = 0.72 USD/m^3 Range = within 20 % of peak	(Heck et al., 2016)
Discount rate	Triangular	Peak = 8 % Range = 6 % to 10 %	(Benalcazar and Komorowska, 2022)

Uncertainty analysis was performed via the Monte Carlo method for provinces with the most favourable, median, and most unfavourable LCOH values for both the solar- and wind-powered systems to account for the variability in costs. Distributions for component costs, price of water, and discount rate were randomly generated according to their assigned distributions in Table 2. Five hundred simulations per location, power source and electrolyser type were done, from which LCOH distributions were generated. The spread of the LCOH values can give information about the level of economic risks that developing green hydrogen plants may have.

3. Results and discussion

LCOH values for solar and wind systems, all provinces in the Philippines and all electrolyser types were calculated. Favourable and unfavourable locations for green hydrogen plants, as well as median LCOH locations, were determined. Monte Carlo simulation results were also presented.

3.1 LCOH calculations

Table 3 shows the summary of the LCOH calculations. Out of the four electrolyser types, SOEC-WH yielded the lowest LCOH at 1.94 – 24.74 USD/kg, followed by AWE (2.36 – 30.11 USD/kg), PEMEC (2.54 – 32.54 USD/kg), and lastly, SOEC (2.75 – 35.33 USD/kg). This implies that the higher capital expenses that will be incurred in using SOEC-WH can be counteracted by the higher efficiencies that come with the additional costs. AWE, being the most technologically mature of the four, can be a viable alternative to SOEC-WH (CapEx = 934.39 USD/kW and OpEx = 64.60 USD/kW-y) for developers with a limited budget as it also has the lowest CapEx and OpEx (743.87 USD and 59.37 USD/kW-y) among the four. The ease of operation can also be a factor in the selection of the right electrolyser as SOEC and SOEC-WH require high-temperature operating conditions and pH of feedstock is important for some of these electrolysers.

Table 3: Summary of the results of LCOH calculations

Power source	Description	Location	Solar GHI (kW/m$^{2)}$ / Wind speed (m/s)	AWE LCOH (USD/kg)	PEMEC LCOH (USD/kg)	SOEC LCOH (USD/kg)	SOEC-WH LCOH (USD/kg)
Solar (resource value is average solar GHI)	Most favourable	Rosario, La Union	0.1998	2.63	2.85	3.15	2.22
	Median	Doña Remedios Trinidad, Bulacan	0.1927	3.49	3.78	4.18	2.95
	Most unfavourable	Mercedes, Camarines Norte	0.1781	3.84	4.16	4.60	3.24
Wind (resource value is average wind speed)	Most favourable	Itbayat, Batanes	8.05	2.36	2.54	2.75	1.94
	Median	Manukan, Zamboanga del Norte	4.12	5.43	5.86	6.36	4.47
	Most unfavourable	Alfonso Lista, Ifugao	2.26	30.11	32.54	35.33	24.74

Solar and wind energy have different location distributions for LCOH. Solar-powered green H_2 has a narrower range than wind-powered green H_2, despite wind having slightly lower values for favourable conditions. This is due to the uniform distribution of sunlight throughout the Philippines compared to the availability of wind in specific coastal areas or areas surrounded by mountains. Higher solar GHI and wind speed lead to lower LCOH.

3.2 Uncertainty analysis

Monte Carlo simulations were carried out by randomly selecting input values such as costs and discount rates with a defined distribution for each. These simulations were conducted for locations with the best, median, and worst values of LCOH, as stated in Table 3, to evaluate the distribution differences between these conditions.

Figures 2 and 3 summarise the results of the Monte Carlo simulations for the SOEC-WH and SOEC systems. The same trends between different conditions were observed for other electrolyser types. The LCOH values for the other electrolyser types are just slightly higher compared to SOEC-WH. The general availability of sunlight is reflected in the closeness of the average capacity factors (CF) for solar-powered systems at 31 to 36 %, unlike in wind-powered systems, where the capacity factors were spread from around 6 % up to 80 %.

Despite having LCOH values of around 2 to 3 USD/kg for good locations, green hydrogen is still more expensive than hydrogen from fossil fuels which can cost 1.0 to 2.5 USD/kg without carbon capture and 1.5 to 3.0 USD/kg with carbon capture (IEA, 2022). However, a price of 2 USD/kg is considered as low enough for green hydrogen to be competitive with grey hydrogen (IRENA, 2021). Unfavourable conditions are also characterised by wider distributions of LCOH, which imply higher risk and lower economic efficiency as changes affect the cost more compared to cases in more favourable locations. Higher energy-to-hydrogen efficiency of the electrolyser and lower costs associated with the components can increase the economic efficiency of the system as observed from the ranges of LCOH for SOEC-WH, which is the best-performing system, and SOEC, which is the worst of the four electrolysers. This implies that economic policy instruments such as subsidies and tax exemptions decrease the risks of developing green H_2 plants by lowering the financial barriers associated with commissioning green H_2 plants. Economic penalties for carbon-emitting systems can also help the competitiveness of green H_2. Aside from these economic policies, the costs and efficiencies of electrolysers, wind turbines and solar PVs are expected to improve via innovative efforts from academic and industrial entities – providing a positive outlook on the competitiveness of green hydrogen (IEA, 2022).

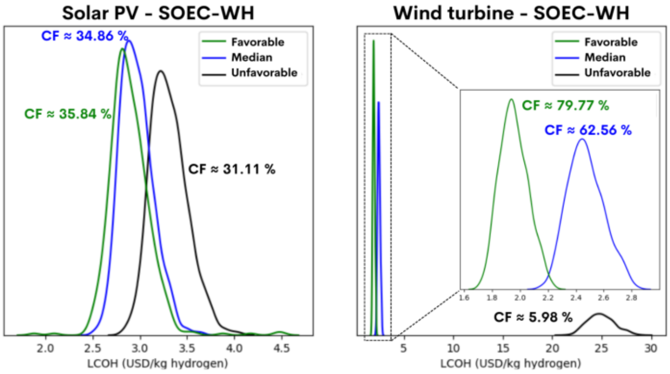

Figure 2: LCOH distribution from Monte Carlo simulations for solar- (left) and wind-powered (right) SOEC-WH

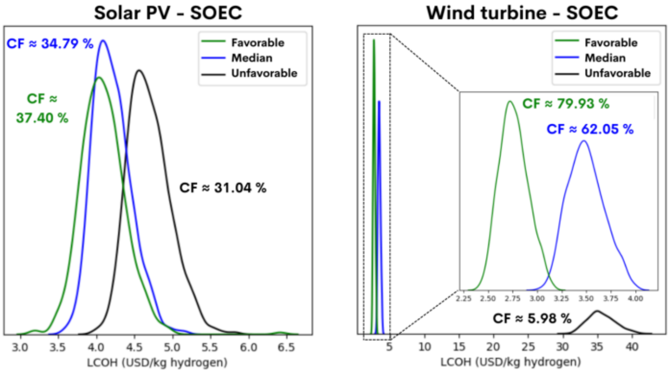

Figure 3: LCOH distribution from Monte Carlo simulations for solar- (left) and wind-powered (right) SOEC

4. Conclusions

The levelized cost of hydrogen was evaluated for all the provinces in the Philippines. LCOH values range from 2.22 to 4.60 USD/kg and 1.94 to 35.33 USD/kg for solar- and wind- powered green H_2 plants. This huge difference in range was attributed to the availability of energy resources. Even for good locations with abundant resources, green H_2 in the Philippines is still expensive with respect to hydrogen from fossil fuels which implies the need for economic policies that will encourage the commissioning of green H_2 plants and renewable energy systems in general within the country's commitment to the Paris Agreement in mind. Uncertainty analysis shows the higher risks tied with developing in locations with scarce resources as a wider range of values in the distribution of LCOH were observed from these locations. Improvements in energy-to-hydrogen conversion and costs due to significant technological advancements will yield a narrower spread of LCOH, implying higher economic efficiency. The issue with the competitiveness of green H_2 can be addressed through economic policies that either incentivise renewable energy systems or penalise carbon emissions. To gain a better understanding of the locations where favourable values for the LCOH have been obtained, it is suggested to conduct a further investigation using higher-resolution data. In addition, it is advised to identify specific systems that are best suited for these locations based on their performance.

Nomenclature

LCOH – levelized cost of hydrogen, USD/kg

NPC – net present cost, USD

W_{H2} – weight of H_2 produced, kg
C_{H2O} – cost of water, USD/m^3
CF – capacity factor, %
CapEx – capital expense, USD/kW
OpEx – operating expense, USD/kW-y
NOCT – nominal operating cell temperature, °C
d – discount rate, %
n – project year, -

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