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Levelized cost of green hydrogen (LCOH) in the Sultanate of Oman using H2A-Lite with polymer electrolyte membrane (PEM) electrolyzers powered by solar photovoltaic (PV) electricity

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Abstract. The techno-economic analysis/assessment (TEA) tool H2A-Lite (Hydrogen Analysis Lite Production) of the United States National Renewable Energy Laboratory (NREL) is applied for computing the levelized cost of hydrogen (LCOH) in the Sultanate of Oman, in the case of utilizing polymer electrolyte membranes (or proton exchange membranes, PEM) in combination with photovoltaic (PV) solar systems. Fourteen parameters (assumptions) were adopted, which include: purchased photovoltaic (PV) green electricity at a fixed rate (tariff) of 0.025 OMR/kWh (0.065 US$/kWh; 1 OMR ≈ 2.6 US$), 64 kWh/kgH_2 (64 kWe/(kgH_2/h)) specific electricity consumption by electrolyzers, OMR 384.6 (US$ 1,000) capital cost per kWe (kilowatt electric) of PEM electrolyzer input-electric capacity, 1 tonne (metric ton; 1,000 kg) of green hydrogen per day (nameplate production capacity), 90% utilization factor, 5 employees with equal individual annual salaries of OMR 26,923 (US$ 70,000), 20 years project lifetime, and straight-line depreciation. The results show that the LCOH is approximately 2.17 OMR/kgH_2 (5.63 US$/kg$H_2$). The corresponding electrolyzer nameplate electric-input capacity is 2.667 MWe (megawatt electric), with actual (not nameplate value) electrolyzer input electric power of 2.400 MWe, and actual (not nameplate value) annual electricity consumption of 21.024 GWh (gigawatt-hours). A sensitivity analysis, with 10% uncertainty, is reported for seven modeling parameters.

1 Introduction

1.1 Hydrogen as a clean fuel or feedstock

Hydrogen as an alternative energy source that is cleaner than hydrocarbon fuels, or as a feedstock gas, has a potential for wide utilization in the future, particularly for environmental reasons to decelerate the climate change [1-3]. Burning hydrogen does not release any carbonaceous greenhouse gases (especially carbon dioxide).

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1.2 Hydrogen production

Hydrogen production based on chemically treating a hydrocarbon fuel may involve emissions of carbon dioxide [4, 5], giving the gaseous product the name gray (or grey) hydrogen (gH). However, hydrogen may also be produced without emissions using a water electrolysis process powered by green electricity (which is electricity generated from a renewable energy source, such as solar energy and wind energy), giving the product the name green hydrogen (GH). Green hydrogen can particularly become beneficial for decarbonizing the transportation sector, through electrification of the transportation vehicles using hydrogen fuel cells [6, 7].

During the water electrolysis process, water is split into gaseous molecular hydrogen and gaseous molecular oxygen through an electrochemical reaction (possibly catalytic) that is endothermic (consumes energy). This required energy is supplied in the form of direct current (DC) electricity. Hydrogen is assembled at the negative electrode (which is the cathode in the case of an electrolyzer) [8-10]. The polymer electrolyte membrane (PEM) technology, also called proton exchange membrane technology, is commonly used for producing green hydrogen commercially; they allow high purity of the produced hydrogen, and they also have relatively high efficiency [11]. In addition, the PEM technology is mature [12], commercially available [13], and operates at moderate temperatures up to about 80 °C [14].

1.3 Green hydrogen plan in the Sultanate of Oman

The Sultanate of Oman is one of the countries that showed an interest in investing in green hydrogen (GH) as global producers and exporters [15], taking advantage of the available renewable energy sources, especially the intense and stable solar radiation [16-18]. The Sultanate of Oman established a national plan for green hydrogen production [19], with the ambition of producing hydrogen according to the growing forecast demonstrated in Table 1.

Table 1. Aimed production of green hydrogen in the Sultanate of Oman.

Year	Million tonnes of green hydrogen per annum (Mtpa)	Electrolyzers capacity, GWe	Renewables capacity, GWe
2030	1-1.25	8-10	16-20
2040	3.25-3.75	35-40	65-75
2050	7.5-8.5	95-100	175-185

Although the “Oman 2040 Vision” does not explicitly mention “hydrogen”; it has emphasis on renewable energy utilization, on environment, and on sustainability; with a target of 20% for the renewable energy consumption percentage of the total consumption in 2030, which increases to 35%-39% in 2050, compared to 0% in 2015 [20]; and this emphasis encourages the country to produce green hydrogen using renewable energy.

In addition, the Sultanate of Oman announced a target of reaching net-zero emissions by 2050 [21], which supports local green hydrogen use as a clean energy carrier instead of petroleum oil or natural gas.

Green hydrogen production in the Sultanate Oman, followed by exporting it directly as a hydrogen derivative (such as ammonia [22]) allows the country to diversify its economy, instead of relying primarily on the revenues of petroleum oil and natural gas [23].

Large-scale green hydrogen investment in the Sultanate of Oman has also social benefits, such as promoting further urbanization through establishing new urban communities near the industrial production facilities, technology transfer to the country, and in-country capacity building.

1.4 Levelized cost of hydrogen

Techno-economic assessment or analysis (TEA) aims at evaluating both technological performance and economic feasibility of a process or a product, especially a new one. One of the useful metrics to economically evaluate the feasibility of green hydrogen production is the levelized cost of hydrogen (LCOH). It is the present value of the cost to produce a unit mass (1 kg here) of hydrogen, when the hydrogen production plant is assessed over its entire lifetime [24]. The LCOH resembles the levelized cots of energy or electricity (LCOE), used for electricity generation power plants. In the case of LCOE, the aim is to the find the overall cost of one unit of generated electricity (such as 1 kWh, kilowatt-hour), expressed in present monetary values [25, 26]. Thus, the LCOH or LCOE is important for identifying the minimum selling price of the product (either hydrogen or electricity).

If the initial capital expense (CAPEX or CapEx) is I_0, the period (year) number is t, the lifetime of the hydrogen production project (in years) is T, the discount rate (inflation rate) is i, the total annual operating expense (OPEX or OpEx) in year t is A_t, and the mass of hydroen produced in year t is M_t; then the following formula describes mathematically how the LCOH can be computed:

$$LCOH = \frac{I_0 + \sum_{t=1}^{T} A_t/(1+i)^t}{\sum_{t=1}^{T} M_t/(1+i)^t} \tag{1}$$

The LCOE has a similar formula, with only replacing the mass of annually produced hydrogen in year t (expressed for example in kilograms of hydrogen, kgH_2) in the denominator by the annually produced electricity in year t, which is designated by E_t (expressed for example in kilowatt-hours of electricity, kWh). Thus, the equivalent LCOE formula is

$$LCOE = \frac{I_0 + \sum_{t=1}^{T} A_t/(1+i)^t}{\sum_{t=1}^{T} E_t/(1+i)^t} \tag{2}$$

It should be noted that Equations (1, 2) are simplified, because possible complexities are not considered in them, such as when the capital cost is not paid once in advance, but is paid in installments during the project operational duration.

In the more-simplified case of: (1) neglected discount rate, (2) fixed annual production mass of hydrogen (M), and (3) fixed total annual expense (A); the LCOH can be obtained using a straightforward equation that does not have a summation series, which is

$$LCOH \approx \frac{I_0/T + A}{M} \tag{3}$$

1.5 Goal of the study

Although LCOH data have been published in other studies, they are based on data focusing on a certain country [27-30]. Therefore, customized LCOH estimates, with accompanying sensitivity analysis, for the Sultanate of Oman seem missing.

The current study provides LCOH results for the Sultanate of Oman, accompanied with a sensitivity analysis. The specific technologies considered here are polymer electrolyte membrane or proton exchange membrane (PEM) electrolysis, and photovoltaic (PV) solar power for electricity generation with a power purchase agreement (PPA).

Aside from presenting techno-economic analysis (TEA) that is specific to one country, the study can be of much broader applicability through the TEA modeling tool described here, which can be used by others for studying many other scenarios pertaining to any other country.

2 Methodology

2.1 H2A-Lite techno-economic analysis tool

The computation of the levelized cost of hydrogen (LCOH), and the related sensitivity analysis of modeling parameters were carried out using a computerized spreadsheet tool for techno-economic analysis/assessment (TEA), called H2A-Lite, which stands for Hydrogen Analysis Lite Production [31]. This is a free interactive Microsoft Excel file, with the extension XLSM, which indicates a special type of Microsoft Excel spreadsheet files that supports macros, which in turn are sets of stored computer instructions for automating computation tasks [32, 33]. H2A-Lite was gratefully made available for download free of charge (after entering some user's information), and it is provided by its owner: The National Renewable Energy Laboratory (NREL) of the United States Department of Energy (U.S. DoE), for internal non-commercial use.

The initial release (version 1.0) of H2A-Lite is dated April 2022. The H2A-Lite version used here is 1.01 (last updated in December 2022). It was downloaded on 22 May 2023 as 16.9 megabytes (MB).

2.2 Input parameters

Computing the LCOH requires supplying various data values (input parameters). The tool H2A-Lite has some default values, which can be conveniently overwritten by the user for customized calculations.

The tool allows 9 modes (technology specifications) of hydrogen production, which are

1. Central Biomass Gasification
2. Central Coal Gasification w/CCS (with carbon capture and storage)
3. Central Grid Electrolysis (PEM)
4. Central Solar Electrolysis (PEM)
5. Central Wind Electrolysis (PEM)
6. Central Grid Electrolysis (Solid Oxide)
7. Central Natural Gas Reforming (no CCS)
8. Central Natural Gas Reforming w/CCS
9. User defined tech

In the last (9^{th}) mode, the user must provide all necessary technology's data. The mode selected here is: 4. Central Solar Electrolysis (PEM). The energy type "Solar" here refers to photovoltaic solar energy, not to concentrated solar power (CSP) [34].

Table 2 lists parameters adopted in the techno-economic simulations. The monetary currency in the model is in US$ (United States dollars), but equivalent values are added in the table in OMR (Omani rials), using the nearly fixed currency conversion (fixed peg) at US$ 2.60 per OMR [35].

Table 2. Parameters used in the techno-economic analysis.

Counter	Parameter	Used value
1	Electricity unit price for the powering the PEM electrolyzers	0.025 OMR/kWh [36] (0.065 US$/kWh)

2	Specific electricity consumption by the PEM electrolyzers	64 kWh/kgH_2 [37, 38] (treated also as 64 kWe/(kgH_2/h)) This means 61.70% higher heating value (HHV) electrolyzer efficiency (based on hydrogen HHV energy content of 39.49 kWh/kgH_2 in H2A-Lite). Alternatively, this means 52.17% lower heating value (LHV) electrolyzer efficiency (based on hydrogen LHV energy content of 33.39 kWh/kgH_2 in H2A-Lite).
3	Capital cost per kWe of PEM electrolyzer input-electric capacity	OMR 384.6 (US$ 1,000) [39] It should be noted that this is not strictly an input parameter in H2A-Lite, but a temporary variable made in the current study to facilitate computing the capital cost (CAPEX) itself, which is the input parameter in H2A-Lite, and it was computed as OMR 1,025,641 (US$ 2,666,667); which is the product of the (capital cost per kWe) and the (computed nameplate electrolyzer capacity; 2,666.67 kWe). This capital cost is assumed to be covered entirely by the stakeholders (equity financing) or by the investor before the hydrogen production plant starts its operation.
4	Nameplate production capacity	1 tonne of green hydrogen per day (1,000 kgH_2/day) Thus, the corresponding nameplate (if full 100% utilization) electrolyzer capacity (electric power input) is 2.66667 MWe.
5	Utilization factor	90% Thus, 90% of the nameplate hydrogen production capacity is actually produced (900 kgH_2/day). And the 365-day annual hydrogen production is 328,500 kgH_2/year. And the hourly hydrogen production (if 24-hour operation per day) is 37.5000 kgH_2/hour.
6	Annual labor cost (fixed operating cost)	5 persons, each receives US$ 70,000 (OMR 26,923) per annum Thus, the total annual labor cost is OMR 134,615 (US$ 350,000).
7	Lifetime of project	20 years
8	Discount rate	0%
9	Loan-to-equity ratio	0

10	Annual or periodic replacements of the installed equipment cost	None
11	Depreciation method	Straight line
12	By-products (Coproducts), such as steam	None
13	Governmental or other incentives	None
14	Enterprise income tax rate	15% [40] (however, this value was found redundant in the analysis, as it did not affect the LCOH in the modeled cases here, since no taxable income is present, either in the baseline case or the two scale-up cases)

Regarding parameter 10 (annual or periodic replacements of the installed equipment cost), it can be viewed as exaggerated to totally neglect any replacement of the PEM electrolyzers throughout the entire lifetime of 20 years. The lifetime of these PEM may reach 10 years [41]. Therefore, one-time replacement at the middle of the project duration is highly anticipated. However, neglecting this situation desirably simplifies the LCOH computation such that Equation (3) becomes valid. The ignored replacement cost can be considered as absorbed in the initial capital cost.

3 Results

3.1 Electricity consumption and cost

The computed electricity consumption results by the central electrolyzer system for different intervals are summarized in Table 3. These electricity consumption values are based on actual operation, not based on nameplate operation (thus computed with the utilization factor taken into account).

Table 3. Expected electric energy consumption (with the utilization factor taken into account).

Duration	**Electricity consumption**
Hour	2,400 kWh/hour
Day (24 hours)	57,600 kWh/day
Month (30 days)	1,728.00 MWh/day
Year (365 days)	21.0240 GWh/year

The corresponding electricity expenses to run the central electrolyzer system are summarized in Table 4.

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Table 4. Expected cost of purchased electric energy (with the utilization factor taken into account).

Duration	Electricity cost
Hour	156 US$/hour (60 OMR/hour)
Day (24 hours)	3,744 US$/day (1,440 OMR/day)
Month (30 days)	112,320 US$/month (43,200 OMR/month)
Year (365 days)	1,366,560 US$/year (525,600 OMR/year)

3.2 PV-PEM LCOH in the Sultanate of Oman

The analysis showed that the levelized cost of green hydrogen (LCOH) is 2.16590 OMR/kgH_2 (5.63133 US$/kg$H_2$).

Figure 1 shows a breakdown of the LCOH. Simply, the LCOH is the sum of three components, which are

1. the annual electricity cost per kg of produced hydrogen (1.60000 OMR/kgH_2, 4.16000 US$/kg$H_2$)
2. the labor cost, which is the fixed operating cost (0.40979 OMR/kgH_2, 1.06545 US$/kg$H_2$)
3. the annual portion of the capital cost when distributed over the lifetime of 20 years (0.15611 OMR/kgH_2, 0.40589 US$/kg$H_2$)

The inflow of equity (which is the sole annual operating revenue) is exactly equal to the dividends paid (which is the sole annual operating expense).

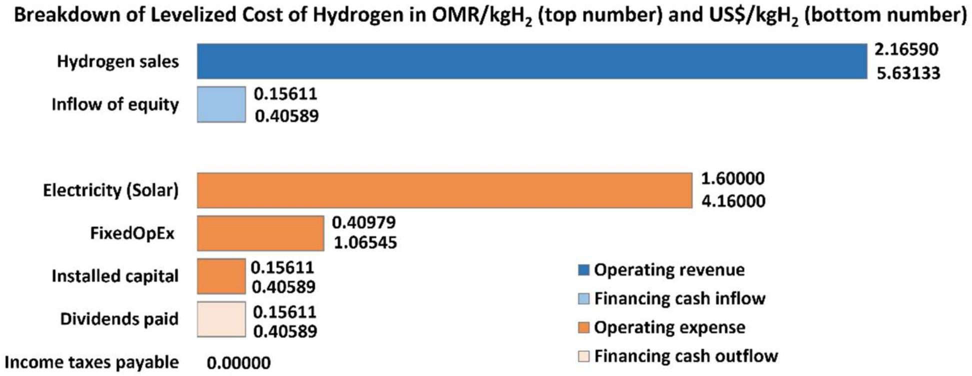

Fig. 1. Breakdown of the LCOH (adapted version of a chart generated by H2A-Lite).

3.3 Sensitivity analysis

H2A-Lite allows performing a sensitivity analysis for some parameters, and this sensitivity analysis is illustrated in Figure 2, with the US$ used as the money currency. The figure is in the form of a tornado chart, showing the expected variation in the LCOH when each investigated parameter changes to 90% and 110% of its baseline value (thus, ±10% uncertainty for each parameter). The LCOH variations are in descending order of their range (minimum-to-maximum), with the widest range at the top, and the narrowest at the bottom.

The relative changes (10% increase or decrease) in the parameter (electricity cost per kWh) and the parameter (specific electricity consumption, kWh/kgH_2) have the same impact on the LCOH. This can be explained by the fact that it is the product of these two parameters that effectively influence the LCOH. These two parameters are equally the most influential ones among the seven investigated parameters. Either of them causes a change in the LCOH from 2.01 OMR/kgH_2 (5.22 US$/kg$H_2$) to 2.33 OMR/kg$H_2$ (6.05 US$/kg$H_2$).

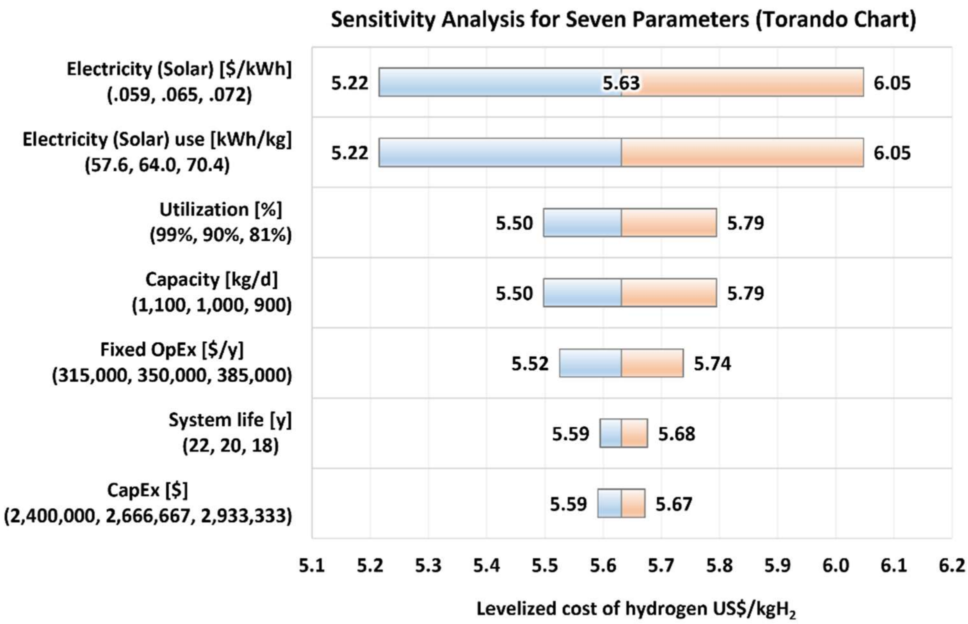

Fig. 2. Sensitivity analysis of seven parameters (adapted version of a chart generated by H2A-Lite).

3.4 Scale-up scenarios

The green hydrogen production in the baseline analysis is 328.5 tonnes per annum (328.5 tpa, or 3.285×10^{-4} Mtpa). Comparing this value to the lower limit of the 2030 target production for the Sultanate of Oman (1 Mtpa) suggests that this baseline hydrogen production plant is relatively not large [42] (but it is also not too small [43]). The estimated capital expense slightly exceeds 1 million OMR (2.6 million US$) in the baseline plant, which may aid in making the green hydrogen production plant achievable for a larger range of investors than a much bigger and costlier plant.

In the present part, two additional computed LCOH values for scale-up scenarios are given. Only the nameplate production capacity is changed in the original baseline model, while all remaining 13 parameters (including the 90% utilization factor) are kept the same. This supplementary part can be beneficial to select large-scale enterprises or governmental bodies interested in the GWe-level of electrolysis capacity (not MWe-level operation). The scale-up results are summarized in Table 5. The baseline results are also given for comparison.

It can be seen that the scale-up reduces the LCOH, but under the assumption that the fixed operating cost (the labor cost) is not scaled up, which means that the same number of employees are running the hydrogen production plant, either in the baseline case or in a scaled-up case. However, if the labor cost is scaled up proportionately with the nameplate hydrogen production capacity, then the LCOH remains the same in the scale-up cases as it was in the baseline case (thus, scaling up does not alter the LCOH).

Table 5. Summary of the baseline scenario of operation, and two scale-up scenarios of operation.

Nameplate production capacity of green hydrogen [tonne per day]	Actual (with utilization factor) annual green of hydrogen production [tonne per annum]	Nameplate electrolyzer capacity [MWe]	Actual (with utilization factor) electrolyzer capacity [MWe]	Actual (with utilization factor) annual electricity consumption [GWh/year]	LCOH [OMR/kgH2] [US$/kgH2], between parentheses
1	328.50	2.66667	2.40000	21.0240	2.16590 (5.63133)
10	3,285.00	26.66667	24.00000	210.2400	1.79709 (4.67243)
100	32,850.00	266.66667	240.00000	2,102.4000	1.76021 (4.57654)

4 Conclusions

The levelized cost of green hydrogen (LCOH) in the Sultanate of Oman was estimated as 2.17 OMR/kgH_2 (5.63 US$/kg$H_2$), for the scenario of purchased solar photovoltaic electricity to operate polymer electrolyte membranes (PEM) for water electrolysis within a central electrolyzer system having a nameplate production capacity of 1 tonne (1 metric ton; 1,000 kg) hydrogen per day, and actual production of 900 kgH_2/day.

The needed nameplate capacity of the central electrolyzers system was found to be 2.6667 MWe (reduces to 2.4000 MWe of actual input electric power if a utilization factor of 90% is assumed).

Supplemental sensitivity analysis (under 10% uncertainty) was also performed for seven input parameters, out of a total of fourteen parameters.

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