Techno-Economic Optimization of e-Hydrogen Production Across Three Cities in Saudi Arabia Using the e-Hydrogen Cost Optimizer

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ABSTRACT

This study applies the e-Hydrogen Cost Optimizer, a Python-based mixed-integer linear programming framework developed at KAUST, to assess the levelized cost of hydrogen (LCOH) at three coastal locations in Saudi Arabia: Baysh, Ras Al-Khair, and Jeddah. Each site was evaluated for three time horizons (2025, 2035, and 2050) under both daily and yearly demand guarantees of 600 tons of hydrogen per day. All techno-economic inputs were drawn from institutional sources, including IRENA, the IEA, the U.S. Department of Energy, and the World Bank. Under the yearly demand guarantee, LCOH declines from 3.02-3.15 $/kg in 2025 to 0.81-0.85 $/kg by 2050, falling below the U.S. Department of Energy target of 1 $/kg, with Jeddah the lowest-cost site in every case. The cost structure is dominated by the electrolyser and photovoltaic capacity, the electrolyser share peaking near 68 percent in 2035 before easing as PEM costs decline. The results were independently reproduced in HOMER Pro, an NREL-developed tool, which agreed with the optimizer to within approximately 5 percent at all three sites. A key limitation of the optimizer, its assumption of constant electrolyser efficiency and no stack replacement, was addressed by quantifying PEM degradation; incorporating efficiency fade and an eight-year stack life raises LCOH by approximately 53 percent uniformly across the three sites, identifying the electrolyser as the decisive long-term cost driver. Finally, a web-based toolkit was developed and deployed to make the optimizer accessible beyond its original desktop application and reproduced the same result.

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1. Introduction

1.1 Background

E-hydrogen is produced by splitting water molecules into hydrogen and oxygen via an electrolyzer powered by renewable energy [1]. It is an essential component of the energy transition, helping decarbonize hard-to-abate sectors to reach net-zero by 2050. However, the levelized cost of hydrogen, which is the total expenditure of a hydrogen facility over its output, is still high, with e-hydrogen produced by PEM and alkaline electrolysis remaining significantly more expensive than fossil-based hydrogen, which is produced at approximately 1.50-3.00 $/kg [2]. Reliable tools to quantify and minimize the LCOH are therefore essential for assessing the commercial viability of e-hydrogen projects. The e-Hydrogen Cost Optimizer was developed at KAUST to meet this need, providing transparent, optimization-based LCOH estimates to support the deployment of e-hydrogen projects in Saudi Arabia and globally [3].

1.2 Objectives

The objectives of this study are to:

1. Assess the levelized cost of hydrogen (LCOH) across three locations in Saudi Arabia using the e-Hydrogen Cost Optimizer.

2. Evaluate three-time horizons: 2025, 2035, and 2050 — to project the long-term cost trajectory of e-hydrogen production.

3. Address a key limitation of the tool by quantifying the impact of electrolyzer degradation on LCOH.

4. Develop and deploy a web-based toolkit for the e-Hydrogen Cost Optimizer to improve accessibility and user experience.

2. Methodology

2.1 Modelling Framework

The techno-economic assessment was carried out using the e-Hydrogen Cost Optimizer, a Python-based mixed-integer linear programming (MILP) framework developed by Dr. Holkan Vazquez-Sanchez at KAUST [3]. The optimizer minimizes the levelized cost of hydrogen (LCOH) by co-optimizing the installed capacities and the hourly dispatch of the system components: photovoltaic (PV) modules, wind turbines, battery storage, a proton exchange membrane (PEM) electrolyser, hydrogen storage, and seawater desalination, which are subject to a specified hydrogen demand. High-resolution (8,760-hour) solar and wind resource profiles for each site were obtained from Renewables.ninja.

2.2 Study Locations and Scenarios

Three coastal locations in Saudi Arabia were evaluated: Baysh in the Jazan region, Ras Al-Khair in the Eastern Province, and Jeddah in the Makkah region. Each site was assessed for three-time horizons, 2025, 2035, and 2050, under two demand-guarantee modes: a daily guarantee, in which a fixed 600 tons of hydrogen must be delivered each day, and a yearly guarantee, in which the equivalent annual quantity is met on an annual basis. This produced eighteen optimization cases in total (three sites, three years, and two demand modes).

2.3 Input Parameters

All techno-economic inputs were obtained from institutional publications. PV and wind turbine capital and operating costs, together with their projections, were taken from the International Renewable Energy Agency (IRENA) Renewable Power Generation Costs series. The PEM electrolyser capital cost, operating cost, and efficiency were drawn from the World Bank (2026), the International Energy Agency (IEA) Global Hydrogen Review (2026), and United States Department of Energy (DOE) technical targets; a 2025 system energy consumption of 52 kWh per kilogram of hydrogen was adopted. The levelized cost of water was based on contracted Saudi independent water project tariffs (Sharakat) and

IRENA, with a water requirement of 17.5 litres per kilogram of hydrogen. A weighted average cost of capital of 5 percent and a project lifetime of 30 years were applied to all cases. Key input parameters are summarized in the tables below.

PV:

Year	CAPEX (USD/kW)	OPEX (USD/kW/yr)	Lifespan	References
2025	725	7.54	25-30	IRENA [4], ACWA [5]
2035	428	4.45	25-30	IRENA [4]
2050	225	2.25	25-30	IRENA [6]

Table 1: Life cycle cost of Photovoltaic technology across different time periods

Wind Turbine:

Year	CAPEX (USD/kW)	OPEX (USD/kW/yr)	Lifespan	References
2025	1713	53	25	IRENA [4]
2035	1370	42.4	25	IRENA [4]
2050	700-1070	21-32	25	IRENA [4]

Table 2: Life cycle cost of Wind Turbine across different time periods

PEM Electrolyzer:

Year	CAPEX (USD/kW)	OPEX (USD/kW.yr)	Efficiency (kWh/kg H2)	References
2025	700-1600	21-48	52	WBG [8], IEA [9]
2030	1000	15-21.9	49	IEA [7]
2050	200	6.45-11.73	46	DOE [10]

Table 3: Life cycle cost of PEM Electrolyzer across different time periods

Water Desalination:

Location	LCOW ($/m3)	Water Efficiency L/kg H2	Technology	References
Jazan Shuqaiq 3 IWP (2025)	0.52	17-18.2	Reverse Osmosis	Sharakat [12], IRENA [13]
Ras Al Khair SA (2025)	0.83	17-18.2	Multi-Stage Flash (MSF)	KAPSARC[11], IRENA, [13]
SaudiArabia 2028	0.48	17-18.2	Reverse Osmosis	SHARAKAT[15], IRENA [13]
Saudi Arabia 2050	0.69	17-18.2	Reverse Osmosis	Caldera [14], IRENA [13]

Table 4: Life cycle cost of water desalination across different time periods

2.4 Independent Validation with HOMER Pro

To verify the optimizer results, the 2025 yearly-demand cases for all three sites were independently reproduced in HOMER Pro, a hybrid-system optimization tool developed by the U.S. National Renewable Energy Laboratory [16]. Component capacities were fixed to the optimizer solution so that the comparison isolated cost-accounting differences from sizing. The PV derating factor was calibrated to match the optimizer's annual specific yield at each site (1,760, 1,671, and 1,731 kWh/kWp/year for Jeddah, Baysh, and Ras Al-Khair). Electrolyzer efficiency was set to 75.8 percent (higher-heating-value basis), equivalent to the 52 kWh/kg used by the optimizer. Because the yearly-demand case constrains only annual output, a zero-cost hydrogen buffer and a small capacity-shortage allowance were added so the hourly HOMER simulation could represent the optimizer's annual-balance constraint.

2.5 Electrolyzer Degradation Assessment

The optimizer application assumes constant electrolyzer efficiency and no stack replacement. To address this limitation, the impact of PEM degradation on LCOH was quantified for the three sites under the 2025 yearly-demand case. Two effects were incorporated using the existing model inputs. First, efficiency fade was represented by raising the specific energy consumption from its beginning-of-life value of 52 kWh per kilogram to a lifetime-average of 54.6 kWh per kilogram, derived from the DOE end-of-life definition of a 10 percent rise in cell voltage. Second, stack replacement was scheduled by reducing the electrolyser lifetime from 30 years to 8 years, obtained by dividing the World Bank PEM stack durability of 40,000 to 60,000 operating hours by the site operating hours of approximately 4,341 sunlit hours per year. The World Bank degradation rate of 0.2 to 0.5 percent per 1,000 hours was used to characterize the fade. The degradation-adjusted cases were then re-solved in the optimizer, and the resulting LCOH was compared with the baseline.

2.6 Web Toolkit Development

The e-Hydrogen Cost Optimizer was originally distributed as a desktop application, which requires local installation and limits access for non-technical users. To improve accessibility, a web-based version was developed that exposes the optimizer's inputs and outputs via a browser interface, allowing users to define scenarios and run LCOH calculations without installing software. The toolkit runs the original optimization model unchanged, a Python (FastAPI) back end using Pyomo with the HiGHS solver, paired with a React front end, containerized with Docker and deployed on KAUST servers (Kubernetes) for internal access.

3. Results and Discussion

The e-Hydrogen Cost Optimizer was used to assess LCOH and produced a result based on the input parameters summarized in Tables 5, 6, and 7.

Scenario 1 – Case 2025

Parameter	Value	Units
Location (coordinates, decimal value)	Baysh; Ras Al-Khair, and Jeddah 17.246504, 42.380500 [Baysh] 27.49367, 49.25886 [Ras Al-Khair] 21.112087, 39.195504 [Jeddah]	Degrees of Latitude and longitude
Simulation lifetime	30	years
Hydrogen demand	600, 000	kg H2 / day
Hydrogen utilization ratio	99	%
Return rate / WACC	5	%
Photovoltaics (PV)	“Saudi Arabia 2025”	–
Wind turbines	“Onshore-Other Asia 2025”	–
Storage	“LFP 2019 (60 MW)–4h”	–
Water desalination (LCOW)	“Saudi Arabia 2025”	USD/m3; L/kg H2
Electrolyzer parameters	“PEM High-Cost High Efficiency-China 2025”	–
Hydrogen storage	“Aboveground tanks – 35 bar”	–

Table 5: Input parameters for LCOH optimization – all three locations, 2025.

Scenario 2 – Case 2035

Parameter	Value	Units
Location (coordinates, decimal value)	Baysh; Ras Al-Khair, and Jeddah 17.246504, 42.380500 [Baysh] 27.49367, 49.25886 [Ras Al-Khair] 21.112087, 39.195504 [Jeddah]	Degrees of latitude and longitude
Simulation lifetime	30	years
Hydrogen demand	600 000	kg H2 / day
Hydrogen utilization ratio	99	%
Return rate / WACC	5	%
Photovoltaics (PV)	“Saudi Arabia 2035”	–
Wind turbines	“Onshore-Other Asia 2035”	–
Storage	“LFP 2019 (60 MW)–4h”	–
Water desalination (LCOW)	“Saudi Arabia 2029”	
Electrolyzer parameters	“PEM High Cost High Efficiency-USA 2030”	–
Hydrogen storage	“Aboveground tanks – 35 bar”	–

Table 6: Input parameters for LCOH optimization – all three locations, 2035.

Scenario 3 – Case 2050

Parameter	Value	Units
Location (coordinates, decimal value)	Baysh; Ras Al-Khair, and Jeddah 17.246504, 42.380500 [Baysh] 27.49367, 49.25886 [Ras Al-Khair] 21.112087, 39.195504 [Jeddah]	Degrees of latitude and longitude
Simulation lifetime	30	years
Hydrogen demand	600 000	kg H2 / day
Hydrogen utilization ratio	99	%
Return rate / WACC	5	%
Photovoltaics (PV)	“Global average 2050”	–
Wind turbines	“Onshore-Global Average 2050”	–
Storage	“LFP 2019 (60 MW)–4h”	–
Water desalination (LCOW)	“Saudi Arabia 2050”	
Electrolyzer parameters	“PEM High Cost High Efficiency-USA 2050”	–
Hydrogen storage	“Aboveground tanks – 35 bar”	–

Table 7: Input parameters for LCOH optimization – all three locations, 2050.

3.1 LCOH Trajectory

The optimization and input results for the three scenarios are represented in Table 8, Figures 1 and 2. Under the yearly demand guarantee, LCOH declines markedly across the study horizon at all three locations, from 3.15, 3.12, and 3.02 $/kg at Baysh, Ras Al-Khair, and Jeddah, respectively in 2025, to 2.91, 2.91, and 2.80 $/kg in 2035, and to 0.85, 0.84, and 0.81 $/kg by 2050. The 2050 values fall below the U.S. Department of Energy target of 1 $/kg [13] and approach the cost range of fossil-based hydrogen. Jeddah returns the lowest LCOH in every case, reflecting its superior specific photovoltaic yield of 1,760 kWh per kWp per year, and the three sites converge by 2050 as photovoltaic and electrolyser costs decline.

The daily demand guarantee produces consistently higher costs than the yearly guarantee, because the requirement to deliver a fixed quantity of hydrogen each day forces additional generation capacity and hydrogen storage. This premium is most pronounced at Baysh and Ras Al-Khair and smallest at Jeddah, where the more uniform solar resource aligns more closely with a constant delivery profile.

Optimization Results – Scenario 1, Case 2025

		Value		
Property	**Unit**	**Baysh**	**Ras Al-Khair**	**Jeddah**
LCOH	$/kg H2	4.04	4.02	3.06
Wind turbines cap.	MW	0	4,632.32	0
PV cap.	MW	8,326.59	7,422.66	11,986.72
Battery power cap.	MW	0	0	0
Battery energy cap.	MWh	0	0	0
Electrolyzer total power	MW	5,891.00	9,118.00	8,629.00
Electrolyzer capacity factor	–	0.26	0.29	0.27
Hydrogen storage	kg	2,587,054	543,495	179,367
Average daily dispatched hydrogen	kg	718,644	1,214,814	1,089,354

Table 8. Optimization results to guarantee daily e-hydrogen demand

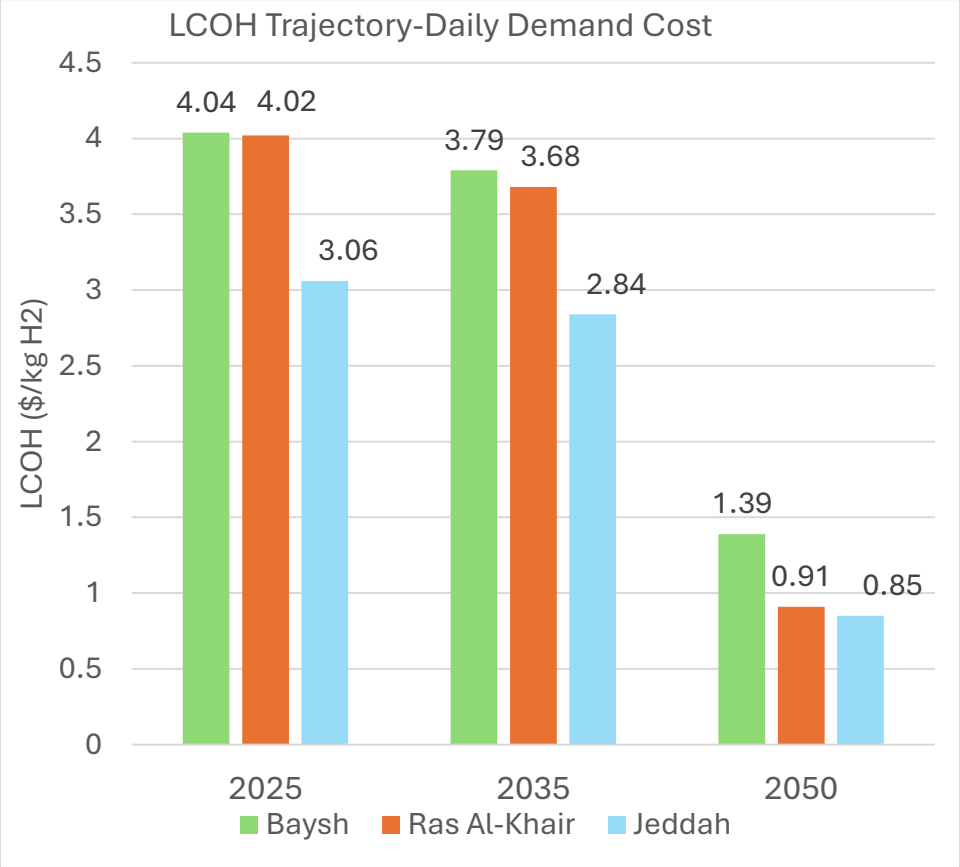


Figure 1: The chart represents the cost of producing one kg of H2 on daily demand basis for all three sites.

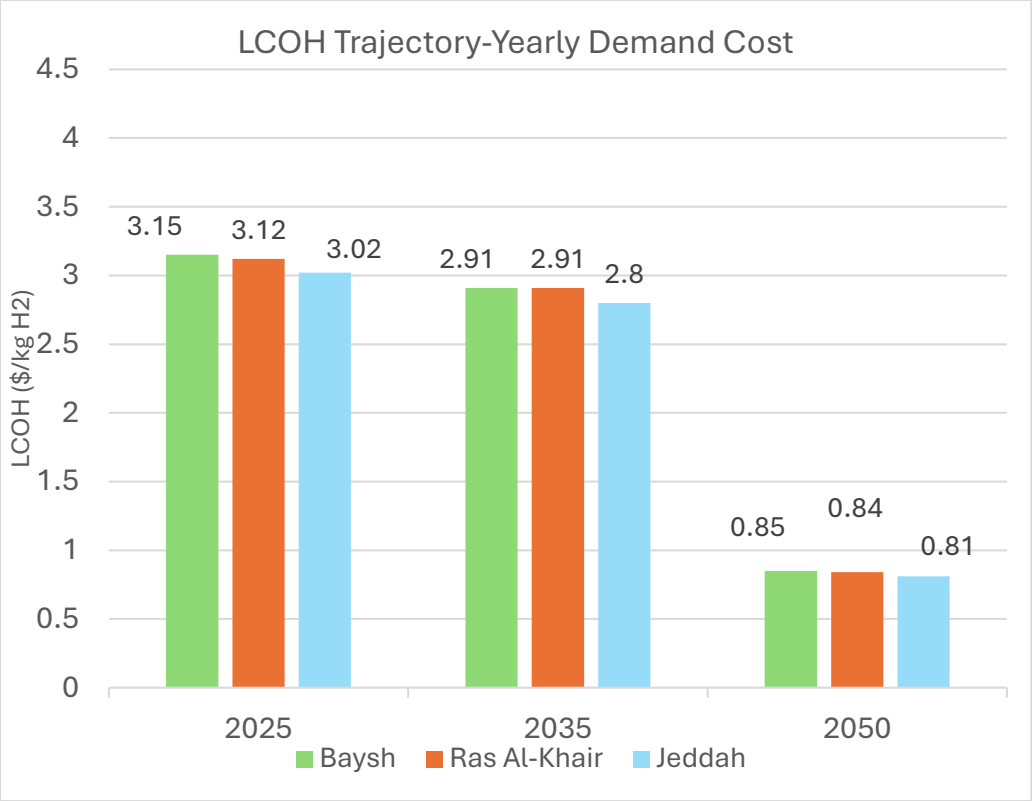


Figure 2: The chart represents the cost of producing one kg of H2 on a yearly demand basis for all three sites

3.2 Cost Breakdown

The cost breakdown shows that the electrolyser and photovoltaic capacity together account for almost the entire LCOH under the yearly demand guarantee, with water desalination contributing consistently less than 1.2 percent at every site and in every year. The relative contribution of the two dominant components shifts over time: the electrolyser rises from approximately 46-48 percent in 2025 to a peak near 68 percent in 2035, before easing to approximately 45 percent by 2050 as PEM capital costs fall more steeply than photovoltaic costs. This pattern is consistent across all three locations and identifies the electrolyser as the principal lever on future cost reductions.

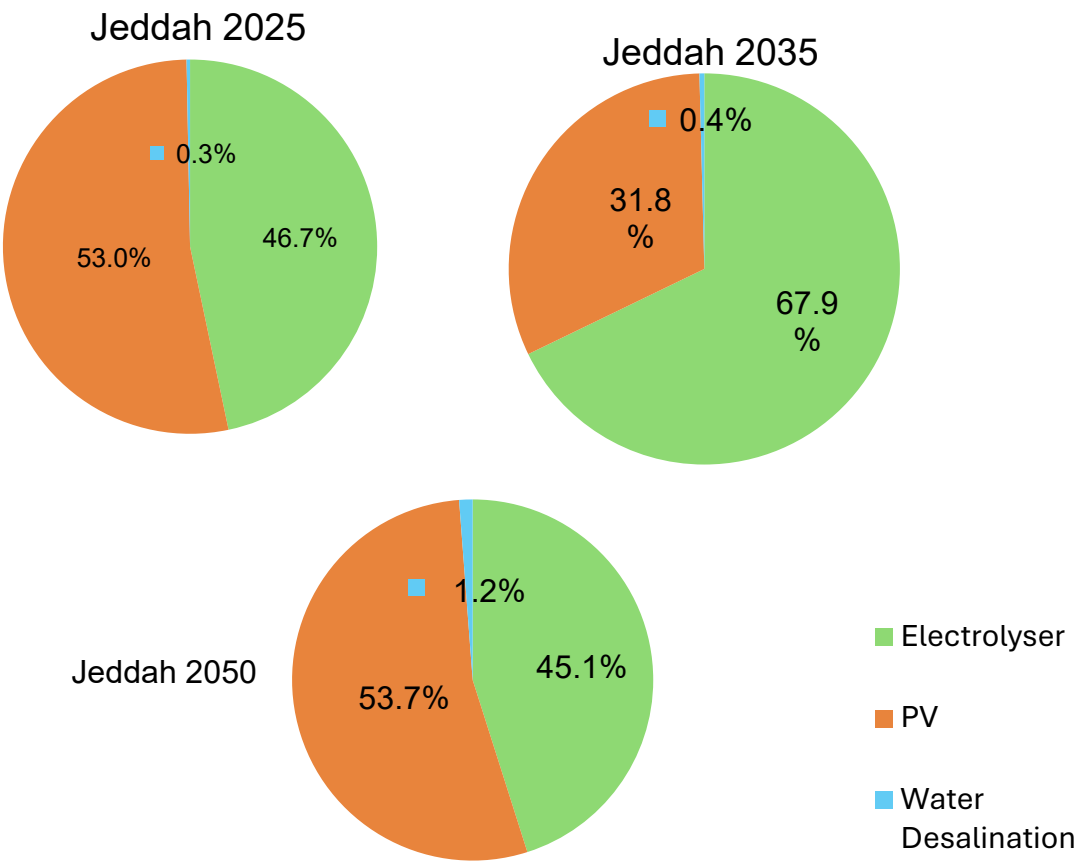


Figure 3: Cost breakdown of LCOH by component for Jeddah across 2025, 2035, and 2050 (yearly demand).

3.3 Electrolyser Degradation Impact

The degradation-adjusted results show that incorporating PEM degradation raises LCOH substantially and almost uniformly across the three locations. Under the 2025 yearly demand guarantee, LCOH increases from 3.02 to 4.61 $/kg at Jeddah, from 3.15 to 4.80 $/kg at Baysh, and from 3.12 to 4.79 $/kg at Ras Al-Khair, corresponding to increases of 52.6, 52.4, and 53.5 percent respectively, an average of approximately 53 percent. The uniformity of this result indicates that degradation is a systemic effect rather than a site-specific one, and it confirms the electrolyser as the decisive long-term cost driver identified in the cost breakdown.

Two qualifications apply to these values. First, the optimizer charges each stack replacement at 100 percent of the electrolyser system capital cost, which represents a

conservative upper bound; the World Bank reports that PEM stack replacement typically costs up to 15 percent of total system cost [11], which would reduce the increase to approximately 15 percent. Second, the degradation rate applied reflects steady-state operation, whereas the U.S. Department of Energy notes that on-off cycling must additionally be considered [13]. As the solar-driven plant modelled here cycles daily, the estimated increase should be regarded as a lower bound on the true degradation impact.

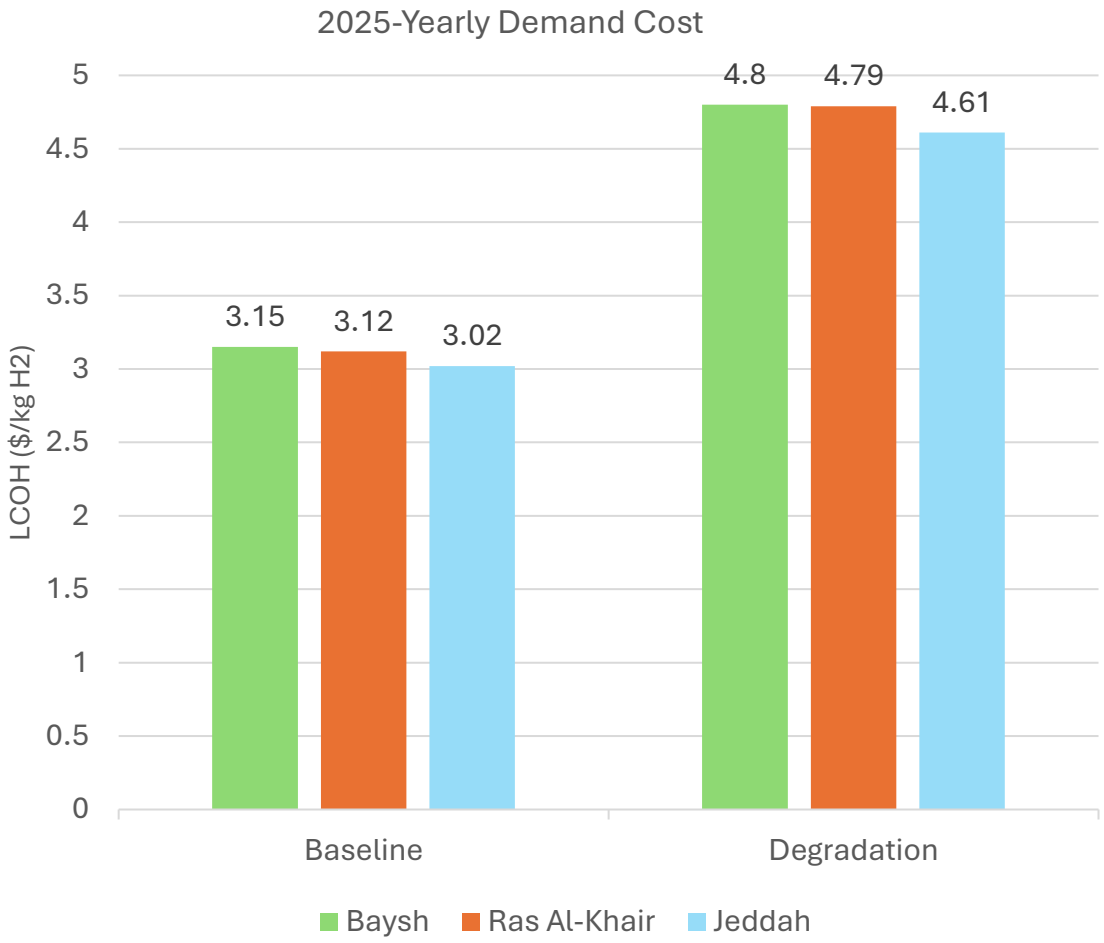


Figure 4: Baseline versus degradation-adjusted LCOH for the three locations under the 2025 yearly demand guarantee.

3.4 HOMER PRO Validation Results

The HOMER Pro simulations reproduced the optimizer results closely at all three locations as shown in Table 9.

Site	Optimizer	HOMER	Δ
Jeddah	3.02	3.09	+2.3%
Baysh	3.15	3.26	+3.5%
Ras Al-Khair	3.12	3.29	+5.4%

Table 9: Comparison of optimizer and HOMER Pro LCOH at Baysh, Ras Al-Khair, and Jeddah, and their changes in percentage (2025, yearly demand).

For the 2025 yearly demand cases, HOMER returned an LCOH of 3.09 $/kg at Jeddah against the optimizer value of 3.02 $/kg, 3.26 $/kg against 3.15 $/kg at Baysh, and 3.29 against 3.12 $/kg at Ras Al-Khair, corresponding to deviations of 2.3, 3.5, and 5.4 percent respectively. Agreement within approximately 5 percent across three independent sites verifies that the cost accounting implemented in the optimizer is reproduced by an established, independently developed tool [22].

The differences are attributable to the solar resource datasets rather than to the cost model. HOMER draws its irradiance from the NASA POWER database, whereas the optimizer uses Renewables.ninja profiles.

3.5 Web-toolkit

The web-based toolkit was successfully developed and deployed on the KAUST server. It reproduces the functionality of the desktop optimizer within a browser, enabling users to enter techno-economic parameters, select locations and scenarios, and obtain LCOH results and cost breakdowns without local installation. The web deployment reproduced the desktop application's results across all cases, while removing the installation barrier and broadening access to the tool.

4. Conclusion

This study assessed the levelized cost of hydrogen at three coastal locations in Saudi Arabia across three time horizons using the e-Hydrogen Cost Optimizer, and reached four principal conclusions.

First, Saudi e-hydrogen becomes cost-competitive over the study horizon. Under the yearly demand guarantee, LCOH declines from 3.02-3.15 $/kg in 2025 to 0.81-0.85 $/kg by 2050, falling below the U.S. Department of Energy target of 1 $/kg [10]. Jeddah returns the lowest cost in every case, and the three sites converge by 2050.

Second, the electrolyser and photovoltaic capacity are the dominant cost drivers, together accounting for almost the entire LCOH, while water desalination remains negligible at less than 1.2 percent throughout. The electrolyser share peaks near 68 percent in 2035 before easing as PEM costs decline.

Third, electrolyser degradation, which the optimizer does not model, has a material effect on cost. Incorporating efficiency fade and an eight-year stack replacement interval raises LCOH by approximately 53 percent uniformly across the three sites, reinforcing the electrolyser as the decisive long-term cost lever.

Fourth, the optimizer results were independently verified in HOMER Pro to within approximately 5 percent at all three sites, with the residual differences traceable to the choice of solar resource dataset rather than to the cost model. Building on this verified basis, a web-based toolkit was developed and deployed to make the optimizer accessible beyond its original desktop application.

For future work, incorporating e-fuels such as ammonia into the optimizer would enable scenarios in which e-hydrogen is converted to and stored as ammonia, a more practical carrier for long-term storage and export.

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