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Optimization of Green Hydrogen Production via Direct Seawater Electrolysis Powered by Hybrid PV-Wind Energy: Response Surface Methodology

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Abstract

This study explored the optimization of green hydrogen production via seawater electrolysis powered by a hybrid photovoltaic (PV)-wind system in KwaZulu-Natal, South Africa. A Box–Behnken Design (BBD), adapted from Response Surface Methodology (RSM), was utilized to address the synergistic effect of key operational factors on the integration of renewable energy for green hydrogen production and its economic viability. Addressing critical gaps in renewable energy integration, the research evaluated the feasibility of direct seawater electrolysis and hybrid renewable systems, alongside their techno-economic viability, to support South Africa's transition from a coal-dependent energy system. Key variables, including electrolyzer efficiency, wind and PV capacity, and financial parameters, were analyzed to optimize performance metrics such as the Levelized Cost of Hydrogen (LCOH), Net Present Cost (NPC), and annual hydrogen production. At 95% confidence level with regression coefficient ($R^2 > 0.99$) and statistical significance ($p < 0.05$), optimal conditions of electricity efficiency of 95%, a wind-turbine capacity of 4960 kW, a capital investment of $40,001, operational costs of $40,000 per year, a project lifetime of 29 years, a nominal discount rate of 8.9%, and a generic PV capacity of 29 kW resulted in a predictive LCOH of 0.124$/kg H_2 with a yearly production of 355,071 kg. Within the scope of this study, with the goal of minimizing the cost of production, the lowest LCOH observed can be attributed to the architecture of the power ratios (Wind/PV cells) at high energy efficiency (95%) without the cost of desalination of the seawater, energy storage and transportation. Electrolyzer efficiency emerged as the most influential factor, while financial parameters significantly affected the cost-related responses. The findings underscore the technical and economic viability of hybrid renewable-powered seawater electrolysis as a sustainable pathway for South Africa's transition away from coal-based energy systems.

Keywords: green hydrogen; seawater electrolysis; hybrid renewable energy; response surface methodology; techno-economic optimization; South Africa

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Academic Editor: Bin Li

Received: 6 August 2025
Revised: 27 September 2025
Accepted: 29 September 2025
Published: 9 October 2025

Citation: Mtolo, S.; Tetteh, E.K.; Mthombeni, N.H.; Moloi, K.; Rathilal, S. Optimization of Green Hydrogen Production via Direct Seawater Electrolysis Powered by Hybrid PV-Wind Energy: Response Surface Methodology. *Energies* **2025**, *18*, 5328. https://doi.org/10.3390/en18195328

1. Introduction

Globally, renewable energy is a key component of cost-effective, environmentally friendly, and sustainable electricity generation. In some countries, it is being used as a substitute for conventional energy sources, such as coal. Investment in renewable energy is crucial for the development of modern economies, as it leads to cleaner environments and reduced carbon dioxide emissions. Countries such as South Africa continue to rely heavily on traditional energy sources like coal, despite the increase in renewable energy generation [1].

South Africa ranks 14th worldwide in CO_2 emissions, with coal making up over 90% of its home energy supply, and this heavy reliance on coal has a significant negative impact on the environment [2]. The country faces challenges with its energy infrastructure, as it is outdated and aging; thus, the grid cannot handle much more power [3]. Therefore, finding an alternative and sufficient renewable energy source that can reduce the usage of coal as a green energy source is significant.

Hydrogen has emerged as a crucial component in the transition to sustainable energy systems. It offers a high-energy-density, zero-emission alternative to fossil fuels. It can reduce carbon emissions in hard-to-abate sectors such as steel manufacturing and long-haul transport. These sectors play a key role in South Africa's economy [2]. However, its environmental benefits are highly dependent on production methods. Conventional steam methane reforming (SMR) remains dominant because it is cost-effective, accounting for 95% of worldwide hydrogen production; however, it releases 9–12 kg of CO_2 for every kg of hydrogen produced [4].

Figure 1 depicts a precise classification of hydrogen production methods based on their environmental impact, ranging from low to high emissions. At the most sustainable end, white hydrogen from natural deposits and green hydrogen produced through renewable-powered electrolysis offer zero-emission solutions. In contrast, pink hydrogen employs nuclear energy for clean production. Transitional solutions, such as blue hydrogen (utilizing steam methane reforming with carbon capture) and turquoise hydrogen (achieved through methane pyrolysis), offer medium-emission alternatives that can help bridge the gap during the energy transition. However, conventional high-emission methods, including gray hydrogen (produced from uncaptured steam reforming) and brown/black hydrogen (derived from coal gasification), remain significant carbon emitters that need to be phased out.

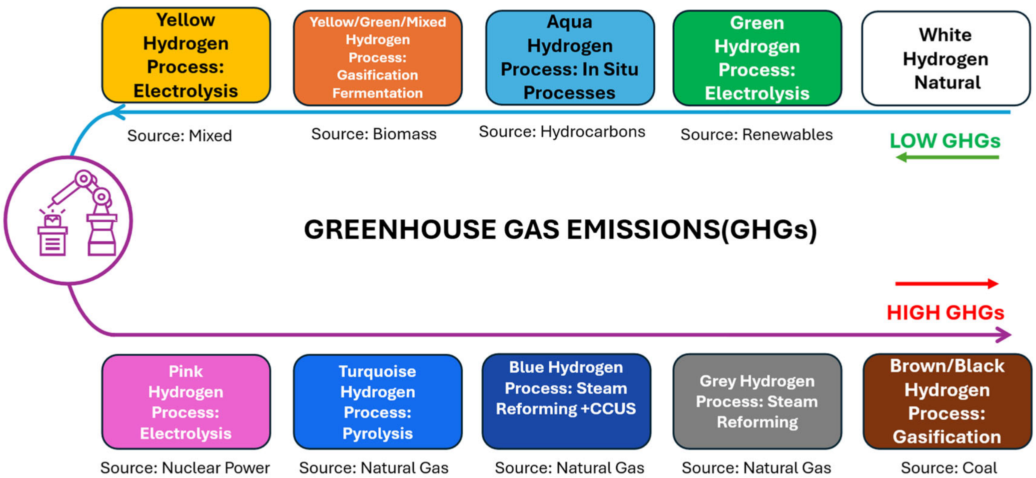


Figure 1. Classification of Hydrogen Production Methods by Source and Carbon Intensity. (Adapted from [5]).

Green hydrogen, produced via water electrolysis powered by renewable energy sources, offers the most sustainable option, and it could lower global CO_2 emissions from 14 kg CO_2-eq/kgH_2 in 2024 to as low as 2–12 kg CO_2-eq/kg H_2 by 2050 [6]. However, challenges such as the intermittency of solar and wind energy resources, the high investment required (both capital and operational costs), and limitations in electrolyzer efficiency hamper large-scale commercialization [5].

Recent research has focused on optimizing the production of green hydrogen within integrated energy systems. For instance, Shen et al. [7] developed a distributionally robust chance-constrained (DRCC) model for an island DC microgrid powered by offshore wind, incorporating a dynamic efficiency model for proton exchange membrane (PEM) electrolyzers to address operational uncertainties. In a broader system context, Zhang et al. pioneered an N-1 evaluation framework for cyber-physical integrated electricity and gas systems (IEGS), highlighting how interdependencies can amplify contingency risks, a critical consideration for future hydrogen infrastructure planning [8]. These studies underscore the importance of robust, cross-system modeling for the secure and efficient deployment of green hydrogen technologies.

Despite the growing global interest in green hydrogen, significant research gaps hinder its development, particularly for water-scarce but coastline-rich nations like South Africa. For instance, studies on hybrid PV-wind systems based on different demographics exist, with a predominant focus on purified water electrolysis [2,9,10], with limited exploration on the application for direct seawater electrolysis [10,11]. This creates a critical knowledge gap for utilizing abundant seawater resources. Although the strong seasonal complementarity of solar and wind resources in South Africa is recognized [12,13], the integrated modeling and optimization of their synergies, specifically for coastal green hydrogen production, remains understudied. Furthermore, the South African power grid, which is predominantly coal-based, is aging and experiences frequent load-shedding events. These conditions lead to repeated start–stop cycles of operational energy patterns that can accelerate cell degradation by affecting catalyst stability and membrane integrity of the electrolyzer when adapted, thereby reducing overall system lifespan and economic viability [14,15]. Also, economic viability studies often lack a holistic approach, failing to fully integrate key techno-economic metrics like the levelized cost of hydrogen (LCOH) and net present cost (NPC) with a computational optimization of a seawater-based system, leading to oversimplified assessments of its scalability [2,3,16]. In addition, South Africa possesses abundant solar and wind resources; however, localized feasibility studies are scarce. For instance, while South Africa's Hydrogen Society Roadmap (HSRM) identifies KwaZulu-Natal as a strategic hub [17], no studies have assessed green hydrogen production using direct seawater electrolysis powered by hybrid renewable energy sources.

In this study, within the South African context, specifically in the KwaZulu-Natal province, the feasibility of seawater electrolysis and cost-optimized green hydrogen production is examined. However, its methodological framework is designed to be adaptable to other regions with similar renewable energy profiles and coastal access. Acknowledging that regional variations in solar irradiance, wind patterns, water quality, and infrastructure may affect the direct transferability of results, this framework is intended to apply to other regions with similar characteristics. It should be noted that advanced materials, such as graphene oxide membranes for electrolysis or pretreatment, represent emerging technologies, typically at low Technology Readiness Levels (TRL < 5). Their costs are currently high, based on lab-scale production, and their long-term durability in industrial seawater applications remains under investigation. The costs used in this model are projections, and their practical integration remains an area of active research and development.

1.1. Regional-Based Green Hydrogen Production

Hybrid Renewable Integration combines photovoltaic (PV) and wind energy to regulate intermittency, leveraging South Africa's abundant solar resources (4.5–6.5 kWh/m^2/day) and strong offshore wind speeds (>9 m/s) [2,18]. This approach aligns with the Integrated

Resource Plan (IRP 2019), which emphasizes diversified renewable energy portfolios to enhance grid stability and sustainability [16]. The integration of hybrid renewable energy systems not only supports green hydrogen production but also offers potential benefits for grid stability. The complementary nature of solar and wind resources can help mitigate intermittency, reducing the strain on South Africa's aging grid infrastructure. However, to fully leverage this advantage, energy storage or buffering systems such as batteries or hydrogen storage itself may be necessary to balance supply and demand, especially during periods of low renewable generation. This aspect is critical for ensuring reliable operation and enhancing the grid's resilience, particularly in regions with limited grid capacity.

Table 1 summarizes key studies addressing South Africa's energy transition challenges and the potential for green hydrogen production. Past research highlights the country's reliance on coal [2,3] and gaps in hybrid renewable integration [2,19], particularly for stabilizing the production of green hydrogen. Studies also underscore seawater electrolysis as a viable solution for regions where water is scarce, with developments in membrane technology reducing corrosion risks [12,20]. However, economic analyses often lack holistic cost assessments, overlooking critical metrics like LCOH and NPC [2]. South Africa's Hydrogen Society Roadmap identifies strategic hubs like KwaZulu-Natal [2], even though localized feasibility studies remain scarce.

Table 1. Techno-Economic and Methodological Advances in Hybrid Renewable Green Hydrogen Systems.

Reference	Location/Year	Main Content (Research Approach and Observation)
[2,3]	South Africa (2025)	Highlighted South Africa's heavy reliance on coal (90% of energy) and grid limitations for renewable integration. Emphasized hydrogen's potential to decarbonize steel and transport sectors.
[2,19]	South Africa (2025)	Identified gaps in hybrid PV-wind modeling for hydrogen production, noting seasonal complementarity but lack of integrated studies for South Africa.
[12,20]	Global (2022–2025)	Critiqued reliance on purified water for electrolysis, proposing seawater electrolysis as a solution for water-scarce regions. Graphene oxide membranes showed promise in reducing corrosion.
[2]	South Africa (2025)	Noted oversimplified economic studies lacking integration of LCOH (Levelized Cost of Hydrogen) and NPC (Net Present Cost) with technical optimization.
[13,21]	South Africa (2025)	The SANEDI-GIZ report and HSRM highlighted KwaZulu-Natal as a strategic hydrogen hub, but lacked localized feasibility studies for coastal seawater electrolysis.
[16,18]	South Africa (2022–2025)	IRP 2019 emphasized hybrid renewables (PV + wind) to leverage solar (4.5–6.5 kWh/m^2/day) and wind (>9 m/s) for grid stability.
[10]	Korea, India (2023)	Demonstrated graphene oxide membranes for seawater electrolysis, addressing chlorine corrosion challenges.
[13]	South Africa (2023)	SANEDI-GIZ report stressed techno-economic gaps between lab-scale research and scalable hydrogen production.

The direct use of seawater for green hydrogen production via electrolyzers is preferable to a freshwater supply and supports Sustainable Development Goal (SDG) 6 (Clean Water and Sanitation) [2,12]. Seawater electrolysis can be made a viable alternative by integrating new types of membranes, like graphene oxide filters, which can effectively reduce corrosion and chlorine evolution challenges [10]. Although the results appear promising, several challenges remain, including high capital costs, electrolyzer degradation, and complexities in grid integration. The findings may provide actionable insights for policymakers and investors. Therefore, exploring seawater electrolysis for green hydrogen production becomes a crucial solution for water-scarce regions [2,10]. The viability of this approach is enhanced by integrating advanced materials like graphene oxide filters, which can effectively mitigate corrosion and chlorine evolution challenges [12].

It is important to note that this initial techno-economic model focuses on the core electrolysis and renewable energy system. The critical aspect of seawater pretreatment (e.g., filtration, desalination) is excluded from the current cost calculations, which is a recognized limitation that would increase the Levelized Cost of Hydrogen (LCOH) in a practical implementation.

1.2. Computational Optimization of Green Hydrogen System

To bridge the gap between small-scale laboratory research and practical implementation, this research employs a Techno-Economic Optimization framework. This approach evaluates the critical balance between technical performance (e.g., electrolyzer efficiency) and financial viability metrics, such as the Levelized Cost of Hydrogen (LCOH) and Net Present Cost (NPC), to identify scalable solutions, as highlighted in the SANEDI-GIZ report [13]. By focusing on the coastal region of KwaZulu-Natal, this research provides a novel, localized blueprint that contributes actionable insights for policymakers and investors. It thereby supports South Africa's Hydrogen Society Roadmap and global efforts to decarbonize energy systems by transitioning away from coal-based energy [13].

Response Surface Methodology (RSM)-based optimization of a hybrid PV-wind system powering direct seawater electrolysis for the South African coastline. The study moves beyond prior work on single resources or purified water by (i) explicitly modeling the unique synergies of South Africa's coastal solar and wind resources for hydrogen production, (ii) evaluating the optimization of direct seawater electrolysis as a solution aligned with SDG 6, and (iii) employing a holistic RSM framework that simultaneously optimizes key technical and economic parameters (LCOH, NPC) for a realistic viability assessment. Methodological approaches such as RSM offer promising optimization pathways [16,18].

This study leverages RSM to optimize green hydrogen production via seawater electrolysis powered by a hybrid photovoltaic (PV)-wind system. Critical variables such as electrolyzer efficiency (A), wind capacity (B), PV capacity (G), and financial parameters (C–F) are analyzed for their impact on key performance metrics, including the levelized cost of hydrogen (LCOH, Y_2), net present cost (NPC, Y_3), and annual production (Y_4). Traditional optimization methods often overlook non-linear interactions or demand excessive experimental runs. Here, BBD efficiently models these relationships, providing actionable insights into the trade-offs between technical performance and economic constraints.

The following research questions were formulated:

- RQ1: How do key operational parameters (electrolyzer efficiency, wind capacity, PV capacity) and financial factors (capital investment, operating costs, discount rate, project lifetime) influence the Levelized Cost of Hydrogen (LCOH) and annual hydrogen production in a hybrid PV-wind seawater electrolysis system?
- RQ2: What is the optimal configuration of a hybrid PV-wind seawater electrolysis system that minimizes LCOH and maximizes hydrogen production while maintaining economic feasibility?
- RQ3: To what extent can direct seawater electrolysis powered by hybrid renewables serve as a sustainable and economically viable alternative to conventional hydrogen production methods in water-scarce regions like South Africa?
- RQ4: How do interactions between technical and economic variables affect the overall system performance and scalability of green hydrogen production?

2. Materials and Methods

2.1. Response Surface Methodology (RSM)

Response Surface Methodology (RSM) is a robust statistical and mathematical approach that evaluates the relationships between multiple input variables and their corresponding responses [17]. It used for modeling, optimizing, and analyzing complex processes. RSM simultaneously minimizes the number of required trials while considering both the individual and interactive effects of the parameters of interest. It is particularly advantageous for experimental designs where efficiency and accuracy are critical [22].

RSM was used to determine the optimal conditions for green hydrogen production via seawater electrolysis powered by a hybrid photovoltaic (PV)-wind system in KwaZulu-Natal, South Africa. This optimization tool assesses both individual parameter effects and their interactions concurrently. Unlike traditional one-factor-at-a-time approaches, RSM provides a comprehensive system behavior by saving time and resources while reducing experimental requirements [23,24].

The Box–Behnken Design (BBD), a subset of RSM, is a rotatable, incomplete multi-factorial design, mainly effective for estimating second-order model parameters with minimal experimental effort. The number of test points is determined by $N = 2k(k-1) + n_c$, where k is the number of factors and n_c represents central repetitions [25]. The inclusion of center points is crucial for estimating pure error and testing model lack of fit; typically, 3 to 5 replicates are recommended to ensure a reasonable estimate of experimental variability and the stability of the model [23,26]. BBD avoids extreme factor-level combinations, providing practical and realistic experimental conditions. It operates with only three levels per factor compared to central composite designs (CCDs), which require 5 levels; thus, BBD reduces complexity and cost without compromising accuracy [23,25].

A literature survey of existing data was used to determine detailed technical and economic input parameters for Design-Expert software (Version 12.0.3.0) [27,28]. The lower and upper limits of the input factors were selected to ensure that both the ranges were experimentally feasible and industrially relevant. The identified bounds for each variable are summarized in Table 2. The model assumed the use of advanced graphene oxide-based membranes, which have shown promise in reducing chlorine evolution and corrosion in seawater electrolysis [27]. While ideal performance was assumed for simplicity, degradation factors were indirectly accounted for through conservative efficiency ranges (80–99%) and operational cost inclusions for the pilot-scale system.

Table 2. Independent parameters and their lower and upper bounds, adapted from the literature [27,28].

Variables	Factor	Units	Range Level			Reference
			−1	0	+1	
Electrolyzer Efficiency	A	%	80	89.50	99	[27,28]
Wind Turbine Capacity	B	kW	100	1050	2000	[27,28]
Capital Investment:	C	$	40,000	60,000	80,000	[27,28]
Operating costs	D	$/yr	40,000	45,000	50,000	[27,28]
Project Lifetime	E	yrs	20	25.00	30	[27,28]
Nominal Discount Rate	F	%	7	8	9	[27,28]
The Generic PV	G	kW	10	505	1000	[27,28]

2.2. Experimental Design and Optimization

The Box–Behnken Design (BBD) was chosen for this study due to its ability to optimize parametric conditions with a minimum number of experimental runs. Unlike other designs, such as Central Composite Design (CCD), BBD maintains computational efficiency and improves the reliability of results by avoiding extreme factor combinations [29].

A three-level BBD was employed to analyze the interactions between the input factors and system responses. The selected independent variables, electrolyzer efficiency (A), wind turbine capacity (B), and capital investment (C), were assigned three equally spaced levels (−1, 0, +1) based on literature-derived operational ranges. Stat-Ease Design Expert-version (12.0.3.0) software was used to improve the RSM model for design-of-experiments (DoE), ensuring accuracy in prediction and optimization.

Appendix A depicts details about the experimental design and structure of a study using RSM. It uses a Box–Behnken design with a quadratic model, optimized for efficiency with 236 randomized runs and no blocking, ensuring robust statistical analysis. This setup was chosen for optimizing renewable energy processes, where non-linear interactions between variables (e.g., electrolyzer efficiency, energy inputs) are explored systematically. The absence of blocks implies a focus on homogeneous conditions, prioritizing unconfounded relationships between variables. The model assumed direct coupling between the hybrid PV-wind system and the electrolyzer, without intermediate energy storage. This simplification enabled a more precise analysis of the renewable electrolyzer interface but may overestimate the impacts of intermittency. Excess electricity and hydrogen were considered as buffers; however, future iterations will incorporate battery storage to reflect real-world system dynamics better.

To address the technical challenges associated with seawater electrolysis, particularly chlorine evolution, electrode corrosion, and membrane degradation, this study incorporates recent advancements in material science that enhance system durability and efficiency. Specifically, we assume the use of graphene oxide-based membranes [27] and non-precious metal catalysts (e.g., nickel-iron layered double hydroxides) [7] to mitigate chlorine corrosion and reduce capital costs. These materials have shown promise in laboratory and pilot studies for improving selectivity toward the oxygen evolution reaction (OER) while suppressing the chlorine evolution reaction (CER) [9,30].

Moreover, the operational parameters optimized in this study (e.g., electrolyzer efficiency, renewable energy input) are modeled under the assumption of advanced electrode coatings and membrane configurations that enhance longevity and performance in saline environments [30,31]. While this study does not experimentally validate these materials, it leverages published techno-economic data to simulate their impact on system performance and cost. Future work will focus on empirically validating these material solutions under real seawater conditions. The validation of the mathematical models was conducted through both internal and external methods. Internally, the models were validated using analysis of variance (ANOVA), lack-of-fit tests, and diagnostic plots (e.g., predicted vs. actual values) to ensure statistical robustness. Externally, the models were compared with independent simulation data not included in the original Box–Behnken Design (BBD), as well as with techno-economic benchmarks from the recent literature on hybrid renewable hydrogen systems (e.g., [2,11,28]). This approach ensured that the models were not only statistically sound but also practically relevant and aligned with existing research.

This study focuses on techno-economic optimization under ideal renewable input conditions; real-world grid faults and intermittent power supply standard in South Africa were not explicitly modeled. Future iterations should incorporate grid reliability metrics and electrolyzer cyclic durability to reflect operational realities better [32]. Furthermore, the Box–Behnken Design (BBD) and RSM approach effectively optimize steady-state performance, the dynamic response of electrolyzers to minute-level renewable energy fluctuations was not explicitly modeled in this study. Future iterations will incorporate high-resolution temporal data and dynamic electrolyzer performance models better to capture the effects of intermittency on efficiency, degradation, and ultimately, the Levelized Cost of Hydrogen (LCOH).

The quadratic model Equation (1) was employed to establish the relationship between input variables and responses:

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{\mathrm{i}=1}^{\mathrm{k}} \beta_{ii} \mathrm{X}_{\mathrm{i}}^2 + \sum_{\mathrm{i}<\mathrm{j}} \beta_{ij} X_i X_j + \epsilon \quad (1)$$

where

Y = Response variable (LCOE, LCOH, NPC, etc.)

β_0 = Intercept term

βi, βii, βij = Linear, quadratic, and interaction coefficients

Xi, Xj = Independent variables

ϵ = Random error

Table 2 shows the independent parameters adapted from [27,28]. Their set ranges for an RSM study are arranged with coded levels (−1, 0, +1) to examine variable interactions in a structured way. The main parameters include electrolyte efficiency (80–99%), wind turbine capacity (100–2000 kW), and capital investment ($40,000–$80,000), which represent technical and economic limits in renewable energy systems. The ranges for operating costs ($40,000–$50,000/year), project lifetime (20–30 years), and discount rate (7–9%) provide more context to the study's focus on technical and economic aspects. The addition of PV capacity (10–1000 kW) highlights a hybrid energy approach. This design enables the optimization of green hydrogen production processes by accounting for non-linear effects and trade-offs among efficiency, scalability, and cost.

A structured approach using Response Surface Methodology (RSM), as outlined in Figure 2, was followed in the optimization process for green hydrogen production via hybrid PV-wind seawater electrolysis by design. This methodology analytically explores the relationships between multiple independent variables and the targeted responses, such as hydrogen yield, levelized cost of hydrogen (LCOH), and net present cost (NPC). The primary objective is to optimize the system to identify optimal operating conditions that strike a balance between technical and economic performance.

It is important to note that the model assumes a direct coupling between the hybrid PV-wind system and the electrolyzer, with no energy storage (e.g., batteries) included. This simplification overlooks the capital cost of storage and associated efficiency losses, but allows for a focused analysis of the core renewable energy–electrolysis synergy. It is acknowledged that for continuous, stable operation mitigating renewable intermittency, energy storage would be indispensable in a real-world application, significantly increasing the Net Present Cost (NPC) and LCOH.

This initial step is crucial, as it establishes the boundaries within which the optimization will operate. The process begins with the selection and definition of independent variables, or inputs, such as electrolyzer efficiency, wind and PV capacity, and financial parameters, including the discount rate and capital expenditures (CAPEX). These variables are assigned with reasonable ranges based on technical constraints and literature data to ensure practical relevance.

A Box–Behnken Design (BBD) is then employed to generate a design matrix for the Design of Experiments (DOE). BBD is a three-level factorial design chosen for its efficiency in reducing the number of simulations run while still capturing non-linear relationships and interaction effects between variables.

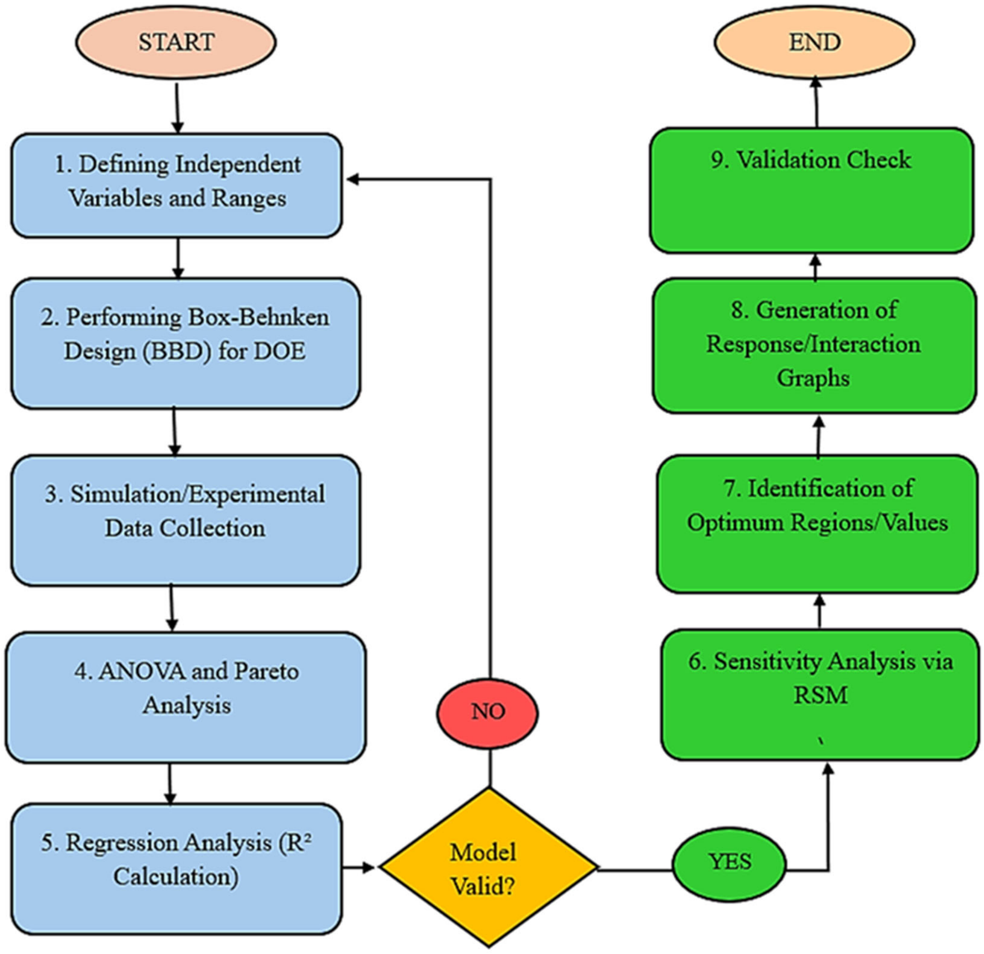


Figure 2. Interactive Flowchart for Hybrid PV-Wind Seawater Electrolysis.

For each combination of variables defined by the BBD, simulation or experimental data was gathered. The responses, such as the yield of hydrogen and LCOH, are recorded and form the basis for further statistical analysis. These data points were used to understand how the system responds under various conditions.

Analysis of Variance (ANOVA) and Pareto analysis were conducted to identify which elements have statistically significant effects on the responses. Factors with *p*-values below 0.05 are deemed necessary, and their relative values are assessed. By concentrating more study on the most critical factors, this stage simplifies the optimization process. Regression analysis follows where quadratic models are developed to characterize the relationships between the responses and the independent variables. Metrics like adjusted R^2 and lack-of-fit tests confirm the validity of these models. A high R^2 value indicates the reliability of the optimization model, as it accounts for a substantial portion of the reaction's variance.

Sensitivity analysis was then carried out to evaluate interactions effects between variables and non-linear correlations. These interactions are visualized using techniques such as 3D surface plots, which also provide insight into how variables synergize or conflict in affecting the responses. This step is crucial for understanding complicated systems where variables do not act independently.

Using the models and sensitivity analyses, the optimal regions or values for the factors were determined. Numerical optimization methods are employed to balance trade-offs between competing objectives, including maximizing hydrogen yield while minimizing LCOH. A desirability function is often used to combine multiple responses into a single metric, facilitating the identification of the best overall conditions. Response and interaction graphs, such as contour plots and 3D graphs, helped to visualize the optimization results and provide an intuitive understanding of the optimal zones. These visual aids are quite helpful in interpreting the results and understanding those outcomes.

2.3. Limitations and Simplifying Assumptions

A key simplifying assumption in this model is the exclusion of capital and operational expenditures for seawater pretreatment. Direct seawater electrolysis requires pre-treatment to remove impurities and salinity, which involves significant costs for filtration, desalination plants, and membrane system [33]. Their omission results in an underestimation of the total system cost and the reported LCOH.

3. Results

3.1. Statistical Approach (ANOVA Results)

Statistical analysis, defined as the process of making scientific interpretations from data that contains variability [34], was validated by analyzing variance (ANOVA). This was conducted to identify the elements that have a statistically significant impact on responses. Significant variables with *p*-values under 0.05; their relative values were evaluated, as depicted in Tables 3–8. Table 9 presents Fit Statistics and Performance Metrics for Energy Response Variables. To determine the reliability of the model, F-values and *p*-values were carefully evaluated. Low *p*-values under 0.05 indicated significant model terms.

Table 3. Analysis of variance for Response 1, LCOE.

Source	Sum of Squares	df	Mean Square	F-Value	*p*-Value	
Model	0.0006	21	0.0000	1.702×10^{6}	<0.0001	significant
A-A:Electrolyzer Efficiency	0.0003	1	0.0003	1.663×10^{7}	<0.0001	
B-Wind Turbine Capacity	0.0000	1	0.0000	2.369×10^{6}	<0.0001	
C-Capital Investment:	0.0000	1	0.0000	2.051×10^{6}	<0.0001	
D-operating costs	0.0002	1	0.0002	1.438×10^{7}	<0.0001	
E-Project Lifetime	1.484×10^{-6}	1	1.484×10^{-6}	87,859.46	<0.0001	
F-Nominal Discount Rate	2.235×10^{-6}	1	2.235×10^{-6}	1.323×10^{5}	<0.0001	
AB	9.001×10^{-8}	1	9.001×10^{-8}	5329.26	<0.0001	
AC	1.541×10^{-7}	1	1.541×10^{-7}	9123.63	<0.0001	
AD	1.094×10^{-6}	1	1.094×10^{-6}	64,784.24	<0.0001	
AE	3.341×10^{-9}	1	3.341×10^{-9}	197.83	<0.0001	
AF	1.008×10^{-8}	1	1.008×10^{-8}	596.73	<0.0001	
BC	2.228×10^{-8}	1	2.228×10^{-8}	1319.01	<0.0001	
BD	7.795×10^{-8}	1	7.795×10^{-8}	4614.76	<0.0001	
BE	9.521×10^{-10}	1	9.521×10^{-10}	56.37	<0.0001	
BF	7.180×10^{-10}	1	7.180×10^{-10}	42.51	<0.0001	
CE	6.601×10^{-8}	1	6.601×10^{-8}	3908.09	<0.0001	
CF	4.970×10^{-8}	1	4.970×10^{-8}	2942.43	<0.0001	
EF	1.114×10^{-9}	1	1.114×10^{-9}	65.94	<0.0001	
B^2	4.036×10^{-8}	1	4.036×10^{-8}	2389.26	<0.0001	
E^2	6.079×10^{-8}	1	6.079×10^{-8}	3598.91	<0.0001	

Table 3. *Cont.*

Source	Sum of Squares	df	Mean Square	F-Value	*p*-Value
F^2	3.512×10^{-10}	1	3.512×10^{-10}	20.79	<0.0001
Residual	3.615×10^{-9}	214	1.689×10^{-11}		
Lack of Fit	3.615×10^{-9}	71	5.091×10^{-11}		
Pure Error	0.0000	143	0.0000		
Cor Total	0.0006	235			

Table 4. Analysis of variance for Response 2, LCOH.

Source	Sum of Squares	df	Mean Square	F-Value	*p*-Value	
Model	0.0417	13	0.0032	1.075×10^5	<0.0001	significant
A-A:Electrolyzer Efficiency	0.0208	1	0.0208	6.959×10^5	<0.0001	
C-Capital Investment:	0.0025	1	0.0025	84,625.94	<0.0001	
D-operating costs	0.0177	1	0.0177	5.939×10^5	<0.0001	
E-Project Lifetime	0.0001	1	0.0001	3609.12	<0.0001	
F-Nominal Discount Rate	0.0002	1	0.0002	5464.73	<0.0001	
G-PV Capacity	0.0002	1	0.0002	5513.52	<0.0001	
AC	0.0000	1	0.0000	381.52	<0.0001	
AD	0.0001	1	0.0001	2713.13	<0.0001	
AF	7.456×10^{-7}	1	7.456×10^{-7}	24.99	<0.0001	
CE	4.766×10^{-6}	1	4.766×10^{-6}	159.75	<0.0001	
CF	3.676×10^{-6}	1	3.676×10^{-6}	123.23	<0.0001	
A^2	0.0001	1	0.0001	4945.09	<0.0001	
E^2	4.313×10^{-6}	1	4.313×10^{-6}	144.55	<0.0001	
Residual	6.623×10^{-6}	222	2.983×10^{-8}			
Lack of Fit	1.862×10^{-6}	79	2.357×10^{-8}	0.7079	0.9542	not significant
Pure Error	4.761×10^{-6}	143	3.330×10^{-8}			
Cor Total	0.0417	235				

Table 5. Analysis of variance for Response 3, Net Present Cost (NPC).

Source	Sum of Squares	df	Mean Square	F-Value	*p*-Value	
Model	4.842×10^{11}	9	5.380×10^{10}	4.448×10^5	<0.0001	significant
C-Capital Investment:	3.200×10^{10}	1	3.200×10^{10}	2.646×10^5	<0.0001	
D-operating costs	2.278×10^{11}	1	2.278×10^{11}	1.883×10^6	<0.0001	
E-Project Lifetime	8.488×10^{10}	1	8.488×10^{10}	7.018×10^5	<0.0001	
F-Nominal Discount Rate	1.349×10^{11}	1	1.349×10^{11}	1.115×10^6	<0.0001	
DE	2.073×10^8	1	2.073×10^8	1713.50	<0.0001	
DF	6.705×10^8	1	6.705×10^8	5543.55	<0.0001	
EF	9.088×10^8	1	9.088×10^8	7513.61	<0.0001	

Table 5. *Cont.*

Source	Sum of Squares	df	Mean Square	F-Value	*p*-Value
E^2	1.915×10^9	1	1.915×10^9	15,835.87	<0.0001
F^2	4.103×10^8	1	4.103×10^8	3392.34	<0.0001
Residual	2.734×10^7	226	1.210×10^5		
Lack of Fit	2.734×10^7	83	3.293×10^5		
Pure Error	0.0000	143	0.0000		
Cor Total	4.842×10^{11}	235			

Table 6. Analysis of variance for Response 4, Annual Green Hydrogen Production.

Source	Sum of Squares	df	Mean Square	F-Value	*p*-Value	
Model	1.035×10^{11}	2	5.175×10^{10}	4.594×10^5	<0.0001	significant
A-A:Electrolyzer Efficiency	1.027×10^{11}	1	1.027×10^{11}	9.114×10^5	<0.0001	
G-PV Capacity	8.278×10^8	1	8.278×10^8	7348.87	<0.0001	
Residual	2.625×10^7	233	1.126×10^5			
Lack of Fit	1.865×10^6	90	20,727.17	0.1216	1.0000	not significant
Pure Error	2.438×10^7	143	1.705×10^5			
Cor Total	1.035×10^{11}	235				

Table 7. Analysis of variance for Response 5, Excess Hydrogen.

Source	Sum of Squares	df	Mean Square	F-Value	*p*-Value	
Model	1.035×10^{11}	2	5.175×10^{10}	4.594×10^5	<0.0001	significant
A-A:Electrolyzer Efficiency	1.027×10^{11}	1	1.027×10^{11}	9.114×10^5	<0.0001	
G-PV Capacity	8.278×10^8	1	8.278×10^8	7348.87	<0.0001	
Residual	2.625×10^7	233	1.126×10^5			
Lack of Fit	1.865×10^6	90	20,727.17	0.1216	1.0000	not significant
Pure Error	2.438×10^7	143	1.705×10^5			
Cor Total	1.035×10^{11}	235				

Table 8. Analysis of variance Response 6, Excess Electricity.

Source	Sum of Squares	df	Mean Square	F-Value	*p*-Value	
Model	3.281×10^{14}	2	1.640×10^{14}	4.594×10^5	<0.0001	significant
A-A:Electrolyzer Efficiency	3.254×10^{14}	1	3.254×10^{14}	9.114×10^5	<0.0001	
G-PV Capacity	2.624×10^{12}	1	2.624×10^{12}	7348.87	<0.0001	
Residual	8.320×10^{10}	233	3.571×10^8			
Lack of Fit	5.913×10^9	90	6.570×10^7	0.1216	1.0000	not significant
Pure Error	7.728×10^{10}	143	5.404×10^8			
Cor Total	3.281×10^{14}	235				

Table 9. Fit Statistics and Performance Metrics for Energy Response Variables.

Fit Statistics	Response 1: LCOE	Response 2: LCOH	Response 3: Net Present Cost (NPC)	Response 4: Annual Hydrogen Production	Response 5: Excess Hydrogen	Response 6: Excess Electricity
Std. Dev.	4.11×10^{-6}	0.0002	347.78	335.63	335.63	18,896.17
Mean	0.0177	0.1507	5.39×10^5	3.38×10^5	2.92×10^5	1.62×10^7
C.V. %	0.0233	0.1146	0.0645	9.94×10^{-2}	0.115	0.1163
R^2	1	0.9998	0.9999	0.9997	0.9997	0.9997
Adjusted R^2	1	0.9998	0.9999	0.9997	0.9997	0.9997
Predicted R^2	1	0.9998	0.9999	0.9997	0.9997	0.9997
Adequate Precision	5980.98	1528.54	2658.81	2063.38	2063.38	2063.38

3.2. Model Equations

Computing and analyzing of the data resulted in response model equations for Y_1: Levelized Cost of Electricity (LCOE), Y_2: Levelized Cost of Hydrogen (LCOH), Y_3: Net Present Cost (NPC), Y_4: Annual H_2 Production Y_5: Excess Hydrogen, and Y_6: Excess Electricity as a function of the input factors (Table 2).

Equations (2)–(7) present quadratic response surface models for optimizing renewable energy and hydrogen production. Process variables A through G influence system performance and economics. Response variables Y_1 to Y_6 measure different aspects of the system. The models have linear terms, interaction terms, and quadratic terms where appropriate. These models (2 to 7) help to optimize renewable energy systems that can produce green hydrogen.

$$\begin{gathered} Y_1 \text{ (Levelized Cost of Electricity} - \text{LCOE):} \\ Y_1 = +0.0176 + 0.0019A - 0.0007B + 0.0007C + 0.0017D - 0.0001E + 0.0002F - 0.0001AB + 0.0001AC + \\ 0.0002AD - 0.0000AE + 0.0000AF - 0.0000BC - 0.0001BD + 5.455E - 06BE - 6.699E - 06BF - 0.0000CE \\ + 0.0001CF + 8.343E - 06EF + 0.0000B^2 + 0.0000E^2 + 2.688E - 06F^2 \end{gathered} \tag{2}$$

$$\begin{gathered} Y_2 \text{ (Levelized Cost of Hydrogen} - \text{LCOH):} \\ Y_2 = +0.1500 - 0.0161A + 0.0056C + 0.0149D - 0.0012E + 0.0014F - 0.0014G - 0.0004AC - 0.0016AD \\ - 0.0002AF - 0.0004CE + 0.0005CF + 0.0017A^2 + 0.0003F^2 \end{gathered} \tag{3}$$

$$\begin{gathered} Y_3 \text{ (Net Present Cost} - \text{NPC):} \\ Y_3 = +5.404E + 05 + 20{,}000.00C + 53{,}363.68D + 32{,}573.75E - 41{,}059.99F + 3599.09DE - 4577.51DF - 7536.58EF \\ - 6155.99E^2 + 2849.23F^2 \end{gathered} \tag{4}$$

$$\begin{gathered} Y_4 \text{ (Annual } H_2 \text{ Production):} \\ Y_4 = +3.375E + 05 + 35{,}824.02A + 3216.85G \end{gathered} \tag{5}$$

$$\begin{gathered} Y_5 \text{ (Excess Hydrogen):} \\ Y_5 = +2.919E + 05 + 35{,}824.02A + 3216.85G \end{gathered} \tag{6}$$

$$\begin{gathered} Y_6 \text{ (Excess Electricity):} \\ Y_6 = +1.624E + 07 - 2.017E + 06A - 1.811E + 05G \end{gathered} \tag{7}$$

where

- Response Variables (Y) are as follows, Y_1: Levelized Cost of Electricity (LCOE), Y_2: Levelized Cost of Hydrogen (LCOH), Y_3: Net Present Cost (NPC), Y_4: Annual H_2 Production, Y_5: Excess Hydrogen, and Y_6: Excess Electricity.
- Process Variables are A: Electrolyzer Efficiency, B: Wind Turbine Capacity, C: Capital Investment, D: Operating Costs, E: Project Lifetime, F: Nominal Discount Rate, and G: Generic PV Capacity.

3.3. Model Performance Evaluation

The predictive accuracy of the developed models was assessed through plots comparing predicted versus actual values for all key response variables. Figure 3 presents the validation results for the Levelized Cost of Hydrogen (LCOH), Net Present Cost (NPC), Annual H_2 production, and Excess Hydrogen production.

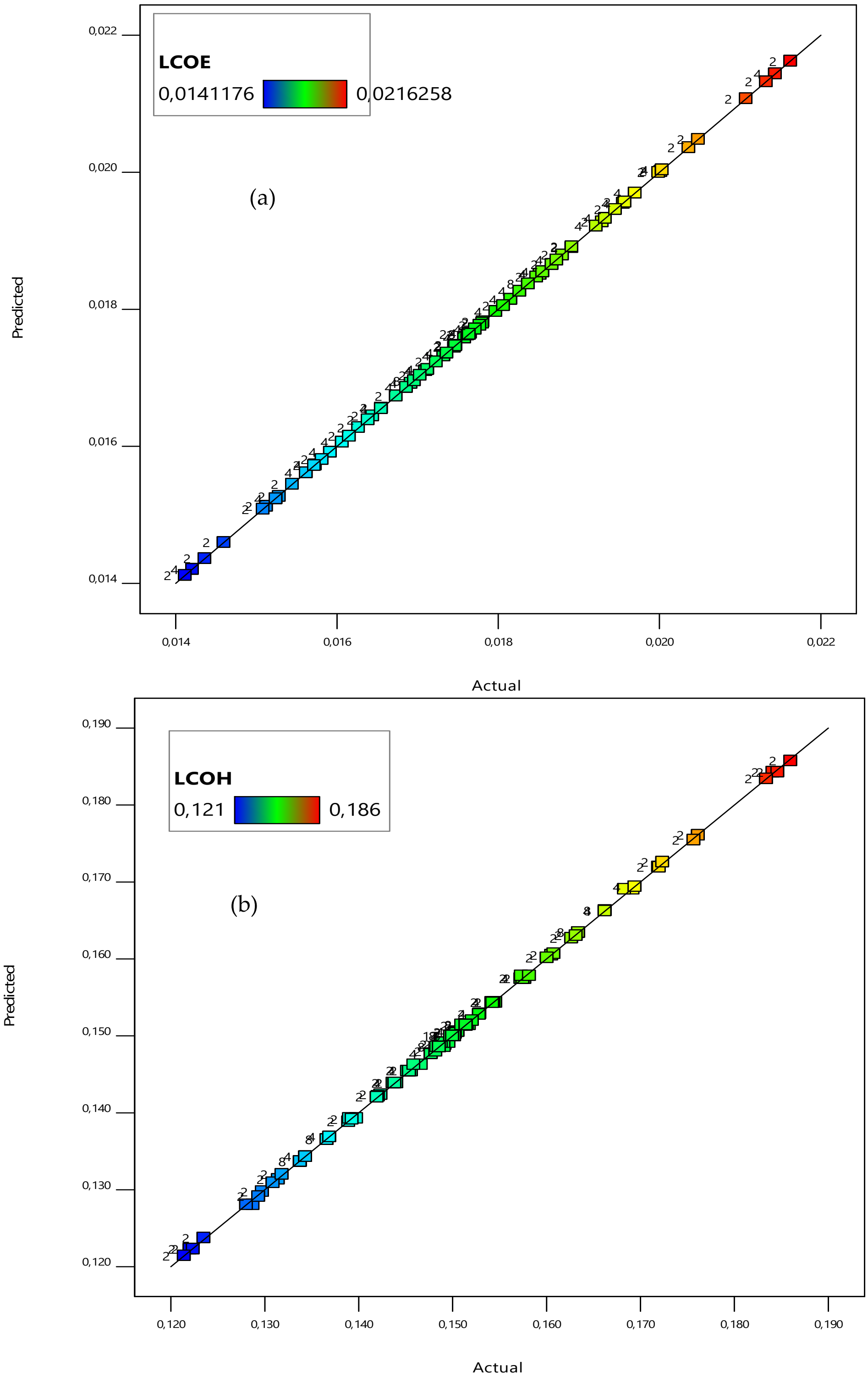


Figure 3. *Cont.*

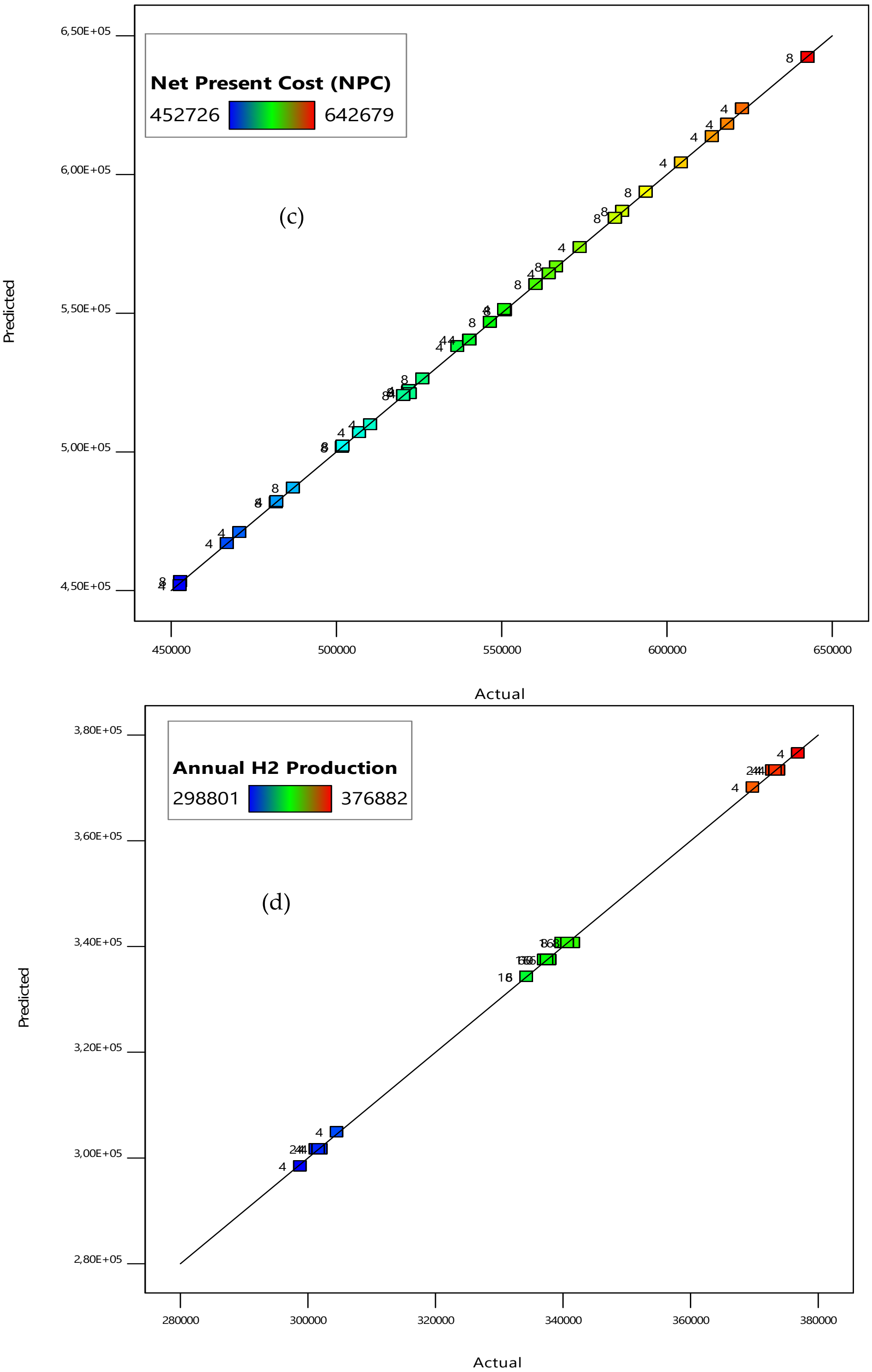
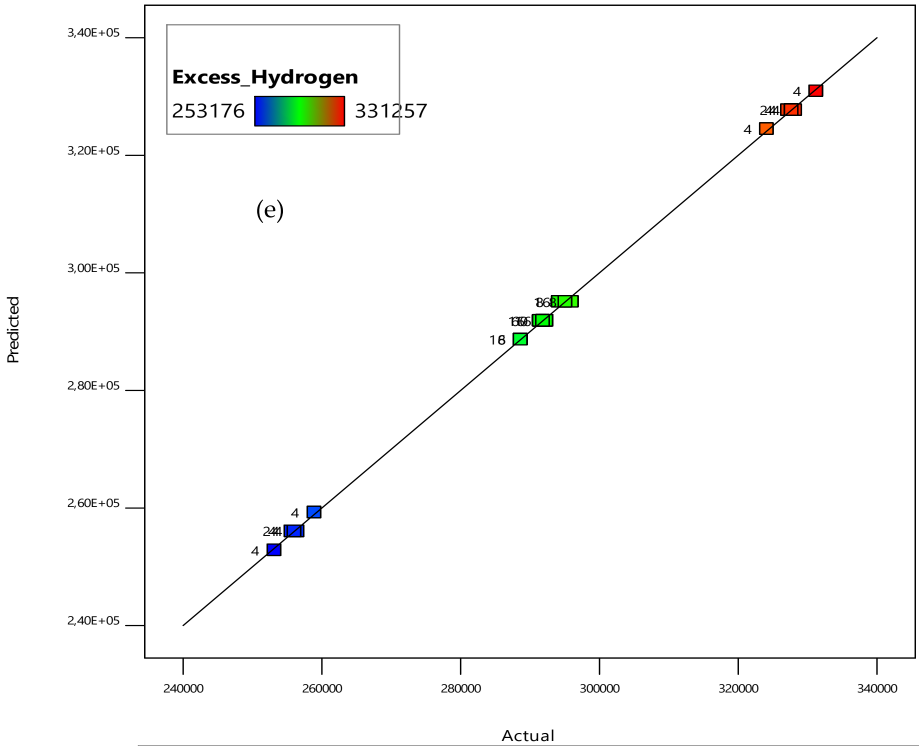


Figure 3. *Cont.*



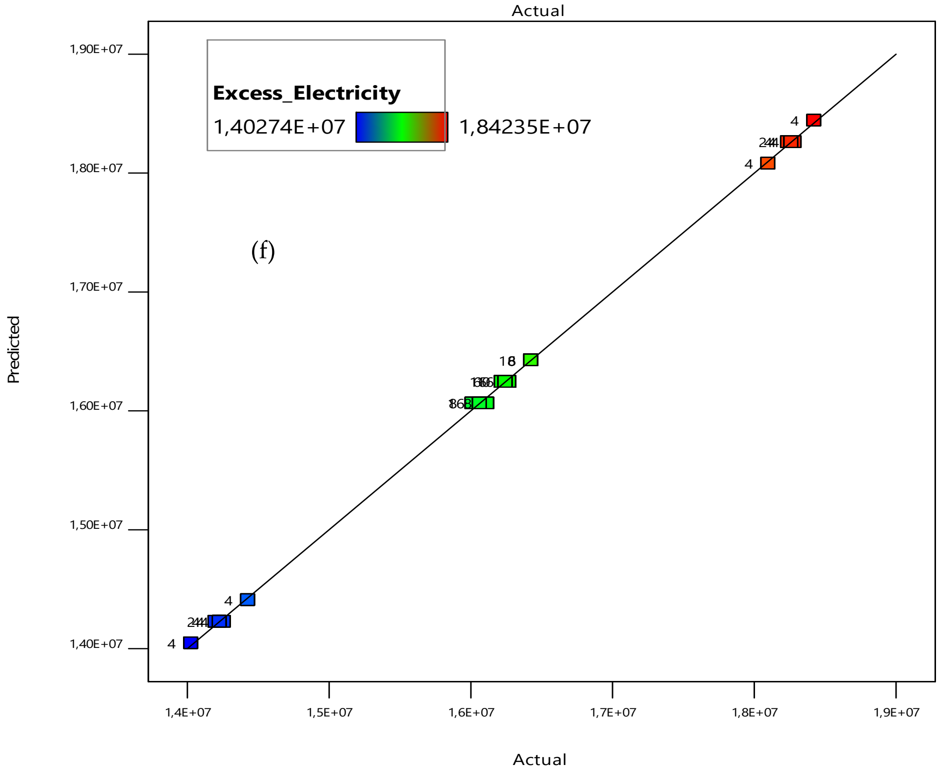


Figure 3. (**a**) Predicted versus actual plots for the validation of Levelized Cost of Electricity (LCOE). (**b**) Predicted versus actual plots for the validation of Levelized Cost of Hydrogen (LCOH). (**c**) Predicted versus actual plots for the validation of Net Present Cost. (**d**) Predicted versus actual plots for the validation of Annual H_2 production. (**e**) Predicted versus actual plots for the validation of Excess hydrogen production. (**f**) Predicted versus actual plots for the validation of Excess electricity production.

3.4. Response Surface Interaction Effects

The following response surface plots illustrate the interaction effects between key design variables on system performance metrics. Figure 4 presents three-dimensional surface plots showing how combinations of input parameters influence the Levelized Cost of Electricity (LCOE), Levelized Cost of Hydrogen (LCOH), Net Present Cost (NPC), and Annual H_2 production across the defined parameter space.

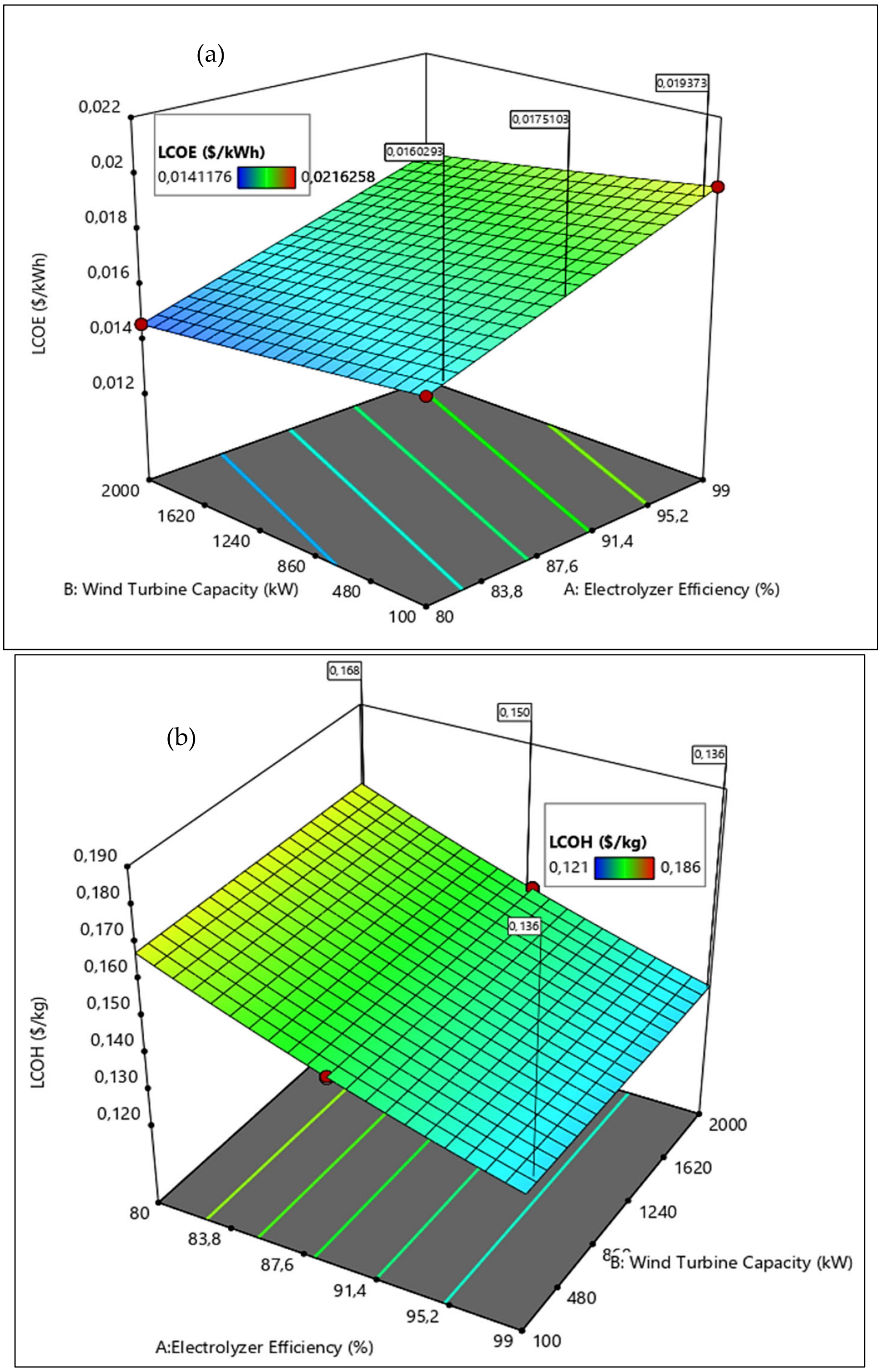


Figure 4. *Cont.*

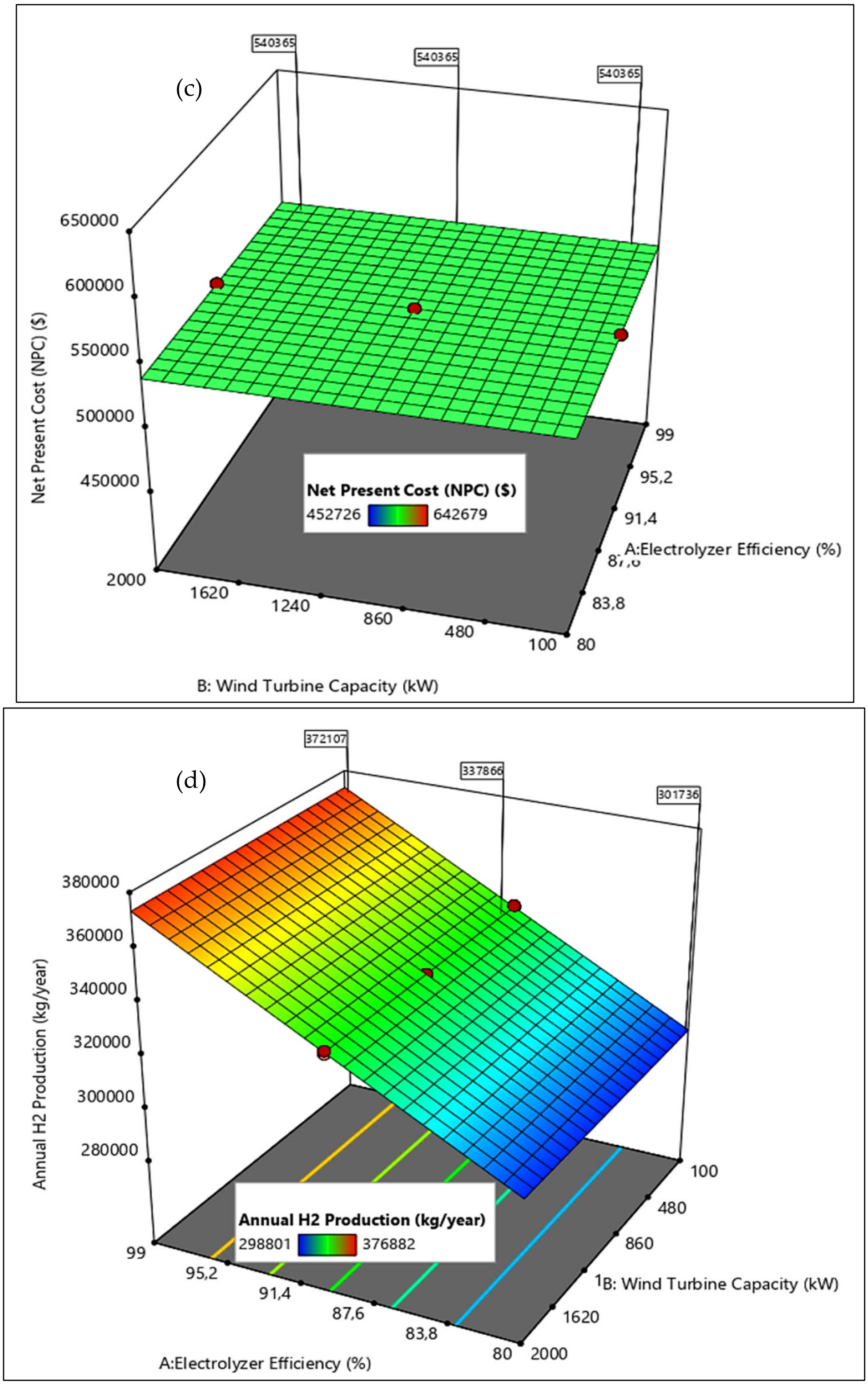


Figure 4. *Cont.*

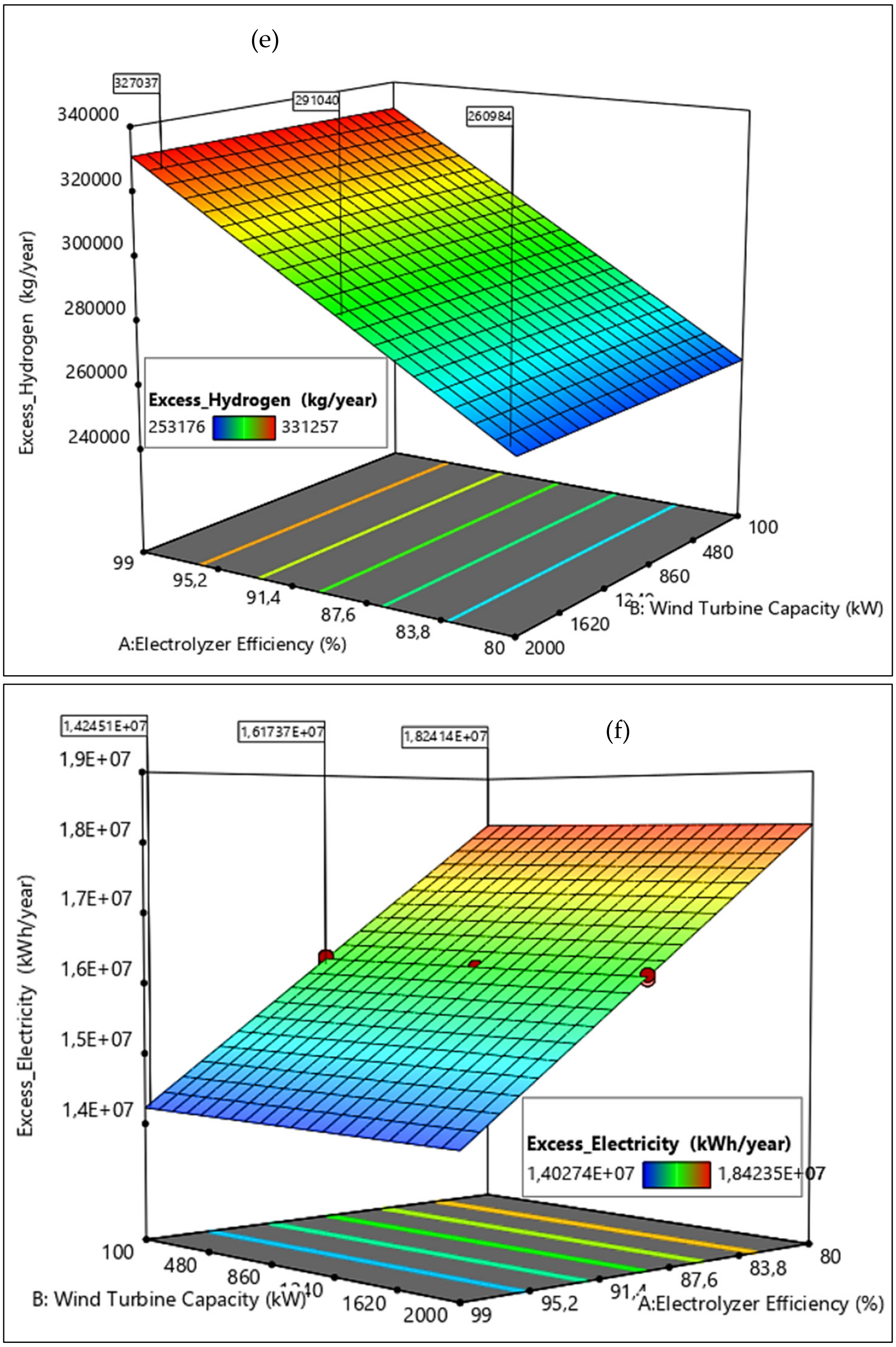


Figure 4. (**a**) Three-dimensional Response surface plots for Levelized Cost of Electricity (LCOE); (**b**) 3D Response surface plots for Levelized Cost of Hydrogen (LCOH); (**c**) 3D Response surface plots for Net Present Cost; (**d**) 3D Response surface plots for Annual H_2 production; (**e**) 3D Response surface plots for Excess hydrogen production; (**f**) 3D Response surface plots for Excess electricity production.

3.5. Optimization Results

Table 10 presents the considerably optimized conditions identified through the response surface methodology. The optimal parameter combinations and corresponding system performance metrics for the top 10 different optimizations scenarios are presented, with a high desirability of 80% at a 95% confidence level. This translates to the most considerable optimal condition, with an electricity efficiency of 95%, a wind-turbine capacity of 4960 kW, a capital investment of $40,001, operational costs of $40,000 per year, a project lifetime of 29 years, a nominal discount rate of 8.9%, and a generic PV capacity of 29 kW. This resulted in a predictive LCOE of 0.014$/kWh, LCOH of 0.124$/kg, NPC of $451,940, H_2 production of 355,071 kg/year, Excess H2 production of 309,522 kg/year, Excess Electricity of 15,251,117 kWh/year.

3.6. Optimization Analysis

Figure 5 presents the ramp plot of the selected optimized condition for the hybrid renewable energy system (HRES). The plot displays the individual parameter effects and their optimal values contributing to the overall system optimization with a desirability of 0.754.

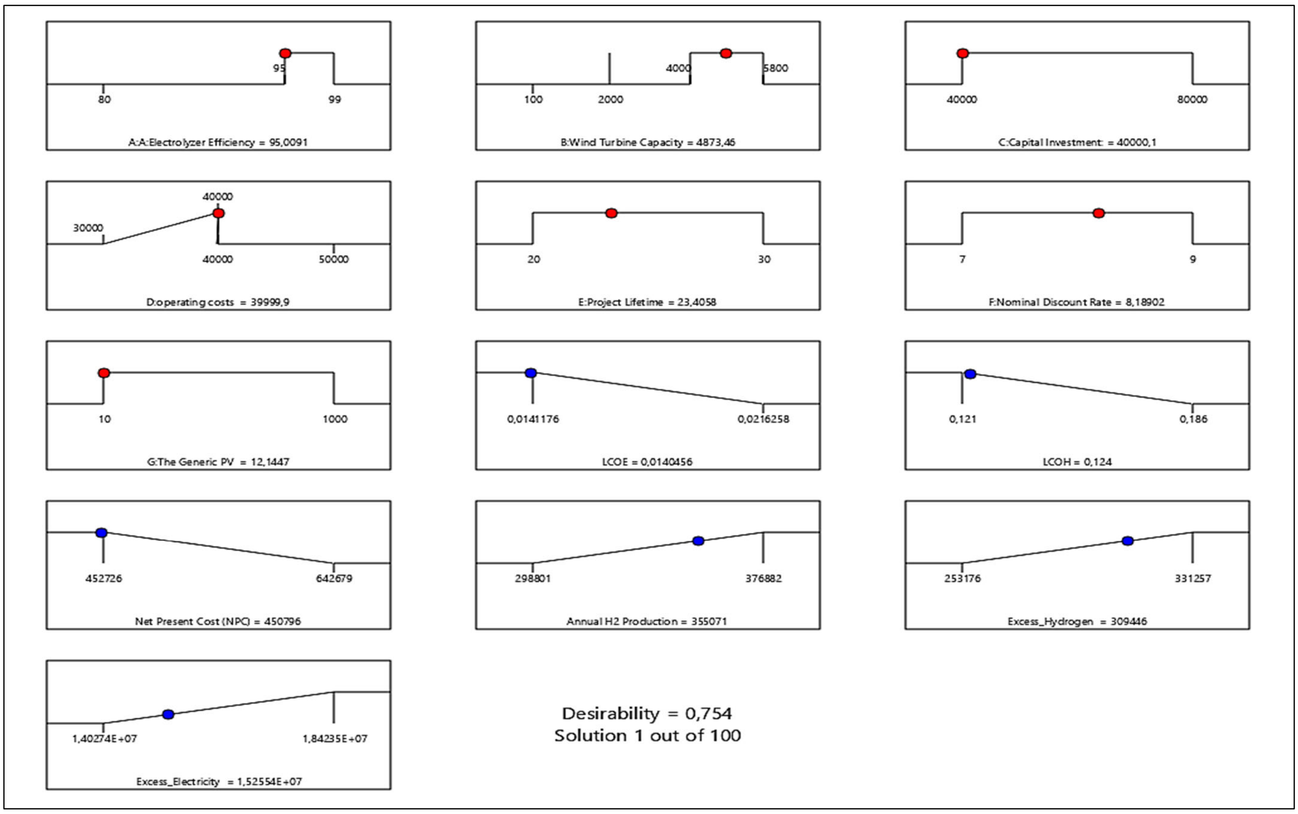


Figure 5. Ramp plot of selected optimized condition of a hybrid renewable energy system (HRES), the red dot-optimum level and blue dot-predicted result level.

Table 10. Considerably best 10 optimal conditions.

Number	A:Electrolyzer Efficiency	Wind Turbine Capacity	Capital Invest-ment:	Operating Costs	Project Lifetime	Nominal Discount Rate	The Generic PV	LCOE	LCOH	Net Present Cost (NPC)	Annual H2 Production	Ecess_Hydrogen	Excess_Electricity	Desirability	Desirability (w/o Intervals)
Units	**%**	**kW**	**$**	**$/yr**	**yrs**	**%**	**kW**	**$/kWh**	**$/kg**	**$**	**kg/year**	**kg/year**	**kWh/year**	**-**	**-**
1	95.00	4960	40,001	40,000	29.0	8.9	29	0.014	0.124	451,940	355,071	309,522	15,251,117	0.8	0.8
2	95.00	5280	40,000	39,980	22.6	8.0	10	0.014	0.124	452,547	355,027	309,402	15,257,916	0.8	0.8
3	95.00	5742	40,001	40,000	21.3	7.7	13	0.014	0.124	452,016	355,045	309,420	15,256,909	0.8	0.8
4	95.03	4752	40,004	40,000	23.3	8.1	58	0.014	0.124	452,600	355,454	309,829	15,233,839	0.8	0.8
5	95.03	5132	40,000	40,000	20.9	7.6	10	0.014	0.124	452,545	355,130	309,505	15,252,100	0.8	0.8
6	95.06	5638	40,000	40,000	25.7	8.6	10	0.014	0.124	448,125	355,234	309,609	15,246,253	0.8	0.8
7	95.04	4938	40,000	40,000	20.0	7.3	10	0.014	0.124	452,491	355,191	309,566	15,248,673	0.8	0.8
8	95.00	5123	40,001	40,000	26.7	8.9	67	0.014	0.124	444,001	355,395	309,770	15,237,164	0.8	0.8
9	95.00	5036	40,002	40,000	20.8	7.5	143	0.014	0.124	452,536	355,888	310,263	15,209,431	0.8	0.8
10	95.00	4885	40,003	40,000	21.0	7.6	161	0.014	0.123	452,551	356,016	310,391	15,202,203	0.8	0.8

4. Discussion

4.1. ANOVA Discussion

Analysis of variance (ANOVA) plays a key role in statistical analysis. It assesses how one or more factors affect the response function, both individually and together. Tables 3–8 show ANOVA results for all responses. ANOVA was conducted to check if the model terms and their interactions were significant for each response variable. The following discussion examines each response in detail, incorporating fit statistics to validate model performance further.

4.1.1. Levelized Cost of Electricity (LCOE)

Table 3 the analysis shows an F-value of 1.702×10^6 ($p < 0.0001$), indicating a very high value that demonstrates excellent predictability by the reduced quadratic model for LCOE. This proves that the reduced quadratic model can predict LCOE well. The efficiency of the electrolyzer stands out as the most significant factor. Its F-value of 1.66×10^7 is high, highlighting its crucial role in minimizing costs. Operating costs and wind turbine capacity also have significant effects on their own. Their F-values were 1.438×10^7 and 2.369×10^6, respectively. Significant interaction terms, mainly AD and AB, revealed synergetic effects between technical and financial parameters. The lack-of-fit test was not significant ($p > 0.05$). This supports the idea that the model is suitable for predicting LCOE. A non-significant lack-of-fit test ($p > 0.05$) confirmed the model's adequacy.

The fit statistics further support the model's robustness, with minimal variability in predictions as indicated by a standard deviation (Std. Dev.) of 4.11×10^6. The coefficient of variation (C.V. %) was remarkably low (0.0233%), indicating high precision. Furthermore, the model achieved perfect R^2, adjusted R^2, and predicted R^2 values of 1, indicating a near-perfect fit. An adequate precision value of 5980.976, which far exceeds the threshold of 4, indicates a strong signal-to-noise ratio.

The exceptionally high F-values observed (e.g., 1.66×10^{10}) indicate an extremely high significance of the respective model terms. This is likely due to the large scale of the data and the high degree of explanation provided by the model for the variance in response. Nevertheless, the model was validated to ensure it is not overfitting and that the assumptions of ANOVA are reasonably met.

4.1.2. Levelized Cost of Hydrogen (LCOH)

The LCOH model in Table 4 showed strong statistical reliability, with an F-value of 1.075×10^5 ($p < 0.0001$). Electrolyzer efficiency and operating costs had the biggest impact on the model, with F-values of 6.959×10^5 and 5.939×10^5. Capital investment also had a significant effect, but it was smaller in comparison (F-value = 84,625.94). The non-linear relationship was indicated by the presence of substantial quadratic terms (A^2 and E^2), particularly concerning efficiency and project lifetime. The lack of fit was statistically insignificant ($p = 0.9542$), further validating the model's reliability.

The model's high precision was shown by the fit statistics, with a standard deviation of 0.0002 and a very low C.V. % of 0.1146. The model demonstrated excellent predictive accuracy, achieving an R^2 of 0.9998, with adjusted and predicted R^2 values also at 0.9998. The adequate precision of 1528.537 confirms the model's effectiveness.

4.1.3. Net Present Cost (NPC)

The NPC model in Table 5 showed strong statistical significance (F-value = 4.448×10^5, $p < 0.0001$). Operating costs and discount rate stood out as main drivers, as their F-values of 1.883×10^6 and 1.115×10^6 prove. Significant interaction terms (DE DF, and EF) highlighted the compounded effects of financial parameters on overall system costs. The lack-of-fit test confirmed the validity of the model, and it showed no significant inadequacies.

The fit statistics (Table 9) supported the model's accuracy showing a standard deviation of 347.78 and a low C.V. % of 0.0645. The R^2 adjusted R^2, and predicted R^2 values of 0.9999 indicate the model has an almost perfect ability to explain the data. The adequate precision of 2658.806 ensures a strong signal-to-noise ratio.

4.1.4. Annual H_2 Production

The annual hydrogen production model in Table 6 showed remarkable significance (F-value = 4.594×10^5 $p < 0.0001$). Electrolyzer efficiency had the biggest impact on the response, with an F-value of 9.114×10^5. PV capacity had a notable but lesser effect, with an F-value of 7348.87. The lack of fit was not significant ($p = 1.0000$), which means the model was adequate. The standard deviation of 335.63 and C.V. % of 0.0994 indicate high precision. The R^2 adjusted R^2, and predicted R^2 values of 0.9997 confirm the model's excellent ability to predict, while the adequate precision of 2063.381 shows a strong model signal.

4.1.5. Excess Hydrogen and Excess Electricity

The excess hydrogen and excess electricity responses in Tables 7 and 8 matched the trends seen in annual H_2 production. Electrolyzer efficiency and PV capacity remained the key individual factors. The same statistical parameters indicate how these factors impact various production-related outputs. For both responses, the standard deviations were 335.63 (Excess H_2) and 18,896.17 (Excess Electricity), with C.V. % values of 0.115 and 0.1163. The R^2 adjusted R^2 and predicted R^2 values of 0.9997 for both models show strong predictive accuracy. The adequate precision of 2063.381 further supports the reliability of the model. The most critical factor that emerged consistently across all responses was an electrolyzer efficiency. This highlights its crucial role in both cost reduction and production optimization.

Financial parameters (capital investment, operating costs, discount rate, and project lifetime) had negligible effects on production and excess energy output but showed dominant effects on cost-related responses. Significant interaction terms revealed complex dependencies between technical and economic variables, emphasizing the need for integrated system analysis. All models showed great predictive power, with R^2 values above 0.99 and lack-of-fit tests that were not significant. The low C.V. % and high adequate precision values further support the reliability of these models. These findings provide clear direction for improving the green hydrogen production system. This means maximizing the electrolyzer's efficiency and how much renewable energy output, while balancing financial parameters for economic viability.

4.2. Mathematical Models

The development of quadratic response surface models (Equations (2)–(7)) provides a robust mathematical framework for understanding and optimizing the complex interplay between technical and economic factors in an integrated renewable energy system for green hydrogen production. The models successfully capture the influence of key process variables (A–G) on critical system performance metrics (Y_1–Y_6), revealing insights that are crucial for strategic decision-making.

4.2.1. Interpretation of Key Economic Models

The models for the primary economic indicators—LCOE (Y_1), LCOH (Y_2), and NPC (Y_3)—are the most complex, featuring a combination of linear, interaction, and quadratic terms. This underscores the non-linear nature of cost dynamics in such systems.

- Levelized Cost of Hydrogen (LCOH–Y_2): This is arguably the most critical response for assessing the viability of green hydrogen. The model shows that Electrolyzer Efficiency (A) and Operating Costs (D) have the most substantial opposing linear effects. Higher electrolyzer efficiency significantly reduces LCOH (coefficient: −0.0161), as it directly improves the conversion efficiency of electricity to hydrogen. Conversely, higher operating costs drastically increase LCOH (coefficient: +0.0149). The presence of a strong positive quadratic term for A (+0.0017A^2) suggests that while improving efficiency is beneficial, the marginal gain in cost reduction diminishes at very high efficiency levels, possibly due to the increasing capital cost of more advanced electrolyzers. The significant negative interaction term between A and D (−0.0016AD) indicates that high electrolyzer efficiency can effectively mitigate the negative financial impact of high operating costs, a vital insight for system designers.
- Net Present Cost (NPC–Y_3): The NPC model is dominated by significant linear coefficients. Capital Investment (C) and Operating Costs (D) naturally increase the NPC, as they represent direct cash outflows. Interestingly, a longer Project Lifetime (E) increases NPC, which may seem counterintuitive. This is likely because the model captures the absolute total cost over the project's life; a longer lifetime incurs more operational expenses, outweighing the benefits of asset depreciation over a more extended period in this specific calculation. The strong negative coefficient for Nominal Discount Rate (F) is a key economic principle: a higher discount rate significantly reduces the present value of future costs, thereby lowering the NPC. The significant interaction terms (e.g., DE, DF, EF) confirm that the combined effect of these financial parameters on the total cost is not simply additive but highly synergistic.
- Levelized Cost of Electricity (LCOE–Y_1): The LCOE model shows smaller magnitude coefficients, reflecting its calculation on a per-unit (kWh) basis. The positive coefficients for A, C, and D indicate that the costs associated with the electrolyzer and system financing directly contribute to the cost of electricity within the integrated system.

4.2.2. Analysis of Production and Excess Outputs

The models for production and excess (Y_4, Y_5, Y_6) are notably simpler, being primarily linear functions.

- Annual H_2 Production (Y_4) and Excess Hydrogen (Y_5): Strikingly, the equations for Y_4 and Y_5 are identical in their variable terms (+35,824.02A + 3216.85G), differing only in their intercepts. This reveals two key insights:
    1. Electrolyzer Efficiency (A) is the overwhelming driver of hydrogen output. A more efficient electrolyzer produces more hydrogen from the same amount of electricity.
    2. PV Capacity (G) also increases production, but to a lesser extent, by providing more energy to the system.

The fact that the models for production and excess are structurally identical suggests that any increase in production leads to a directly proportional increase in excess hydrogen, assuming demand is constant. This highlights a potential need for optimized storage or demand-side management to utilize this excess.

- Excess Electricity (Y_6): This model has a large negative coefficient for Electrolyzer Efficiency (A) and PV Capacity (G). This indicates that a more efficient electrolyzer consumes more of the available electricity, leaving less excess. Similarly, counterintuitively, more PV capacity reduces excess electricity. This is because Equation (7) likely represents the net excess after the electrolyzer's demand is met. A larger PV array might be paired with a larger or more efficient electrolyzer that consumes the additional generation, thereby reducing the net excess sent to the grid or curtailed.

4.3. Implications for System Optimization

The derived models are not merely descriptive but are prescriptive tools for optimization. The presence of quadratic and interaction terms in the cost functions (Y_1, Y_2, Y_3) confirms that the system possesses a non-linear response surface with identifiable minima (optimal points). For instance, the quadratic term for A in the LCOH model suggests an optimal electrolyzer efficiency beyond which further investment may not be cost-effective.

Furthermore, the strong interaction effects, such as between discount rate and other costs in the NPC model, imply that optimization cannot be performed on a single variable in isolation. A holistic approach, considering the combined settings of technical efficiency (A, G), capital investment (C), and financial parameters (E, F), is essential to find the global optimum that minimizes LCOH while managing capital exposure (NPC).

This study's theoretical and simulation-based framework for optimizing seawater electrolysis powered by hybrid PV-wind systems has key limitations that define the future research agenda. The models rely on simulated data and linear simplifications that may miss non-linearities at design extremes. At the same time, the absence of pilot-scale validation overlooks critical real-world factors like electrolyzer degradation, seawater corrosion, and grid integration challenges. Furthermore, the current model assumes constant renewable energy availability and does not explicitly account for the intermittency of solar and wind resources, grid integration challenges, or the need for energy storage systems. These simplifications may lead to optimistic estimates of hydrogen production and cost. Future iterations of this model will incorporate real-time weather data from the KwaZulu-Natal region and include energy storage (e.g., batteries) and grid-balancing mechanisms to reflect real-world operational dynamics better.

4.4. Model Performance Evaluation

4.4.1. Economic Parameters

The model displayed outstanding predictive performance for both the Levelized Cost of Electricity (LCOE) and Levelized Cost of Hydrogen (LCOH). In Figure 3a, the data points line up along the diagonal, which indicates a strong link between predicted and actual LCOE values. This suggests the model's predictions were accurate, with minimal scatter observed from 0.014 to 0.022$/kWh. Similarly, in Figure 3b, the predicted values maintain excellent agreement with actual values across the entire spectrum. This proves the model is just as good at predicting LCOH, with values ranging from 0.121 to 0.186$/kg.

The calculated LCOH of 0.124$/kg is notably lower than international benchmarks. This discrepancy is primarily attributable to the exclusion of seawater pretreatment costs, as discussed in Section 2.3. A preliminary estimate based on the literature suggests pretreatment could add approximately $3.44–$3.55/kg to the LCOH [33], aligning the total cost more closely with the expected range of $3–$8/kg. Future work will integrate these costs for a more comprehensive analysis.

4.4.2. Cost and Production Parameters

The Net Present Cost (Figure 3c) shows great model accuracy. Predicted values match actual values from $450,000 to $650,000. The straight-line relationship indicates the economic modeling framework captures cost dynamics well. Figure 3d displays the Annual H_2 production validation. It demonstrates good prediction accuracy for production levels from about 280,000 to 380,000 kg/year.

4.4.3. Excess Resource Parameters

There is a good correlation of the model's ability to predict excess hydrogen production (Figure 3e) from 240,000 to 340,000 kg/year. However, it shows greater variability compared to the primary economic variables or parameters. The closeness of the points to the diagonal line indicates that the model obtains hydrogen production dynamics under varying operational conditions. Figure 3f depicts the validation for excess electricity predictions from the range of 1.4×10^7 to 1.9×10^7 kWh/year.

The thorough validation across these six key factors shows how robust and reliable the predictive model is. The strong linear correlations observed in all predicted versus actual plots, with minimal scatter and consistent alignment along the diagonal, indicate that the model successfully captures the underlying physical and economic relationships within the system. The slight variations observed in the excess resource predictions (hydrogen and electricity) might reflect the natural complexity and variability in renewable energy systems, where production surpluses are affected by many random factors, including weather patterns and shifts in demand. The color gradient (from blue to red) across all plots indicates that the model maintains its predictive accuracy across different operational regimes and boundary conditions. This is key to putting it into practice and to study how to make it better. This validation provides confidence in the model's applicability for design optimization, economic feasibility studies, and operational planning of renewable energy-based hydrogen production systems.

The color-coded progression from blue to red across all plots suggests that the model maintains its predictive accuracy across different operational regimes and boundary conditions, which is crucial for practical implementation and optimization studies. This validation provides confidence in the model's applicability for design optimization, economic feasibility studies, and operational planning of renewable energy-hydrogen production systems.

A key limitation of this economic model is that it did not include the capital and operational costs associated with seawater pretreatment. For direct seawater electrolysis to be feasible, essential pretreatment processes such as filtration, reverse osmosis (RO) desalination, and purification are required to remove impurities, suspended solids, and ions that cause catalyst poisoning and membrane degradation [35,36]. The omission of these costs means the LCOH estimated values represent a lower-bound estimate. Including pretreatment would inevitably increase the final LCOH. Future work must integrate a detailed costing model for seawater pretreatment systems, drawing on data from the desalination industry [37,38]. To provide a more accurate and comprehensive techno-economic assessment of coastal green hydrogen production.

The omission of energy storage costs contributes to the low NPC and LCOH values reported. Integrating battery storage would incur substantial additional capital costs and reduce overall system efficiency due to charge–discharge cycles. A sensitivity analysis including storage costs is recommended for future work to quantify this impact.

4.5. Response Surface Interaction Effects

The 3D interaction plots in Figure 4a–d show how key operational parameters affect system performance. The color gradients in these plots make it easy to see output changes. Blue areas illustrate lower values, while red areas depict higher values. This assists in locating the best conditions.

Figure 4a illustrates the interaction between electrolyzer efficiency (A) and wind turbine capacity (B) on hydrogen production. The response surface indicates that hydrogen output is maximized at high electrolyzer efficiencies paired with intermediate wind turbine capacities. This underscores the critical role of electrolyzer performance in the system.

Conversely, the diminishing returns observed at high wind capacities suggest that oversized turbines represent a suboptimal allocation of capital resources, highlighting the importance of right-sizing components to avoid unnecessary expenditure.

Figure 4b presents the combined effect of electrolyzer efficiency (A) and operating costs (D). The analysis confirms that enhanced electrolyzer efficiency significantly improves system output. However, the steep gradient of the surface at lower efficiency levels indicates that marginal improvements in electrolyzer technology can yield substantial performance gains. To maintain economic viability, these efficiency gains must be evaluated against the associated operating expenses, as profitability is highly sensitive to this trade-off.

Figure 4c depicts the relationship between wind turbine capacity (B) and system cost. The non-linear, convex nature of the curve demonstrates a point of increasing marginal cost. Beyond a certain capacity threshold, the financial investment required escalates rapidly relative to the incremental gains in capacity. This economic phenomenon necessitates the identification of an optimal turbine size that minimizes the levelized cost of energy or hydrogen.

Figure 4d explores the synergistic effect of wind turbine capacity (B) and PV capacity (G) on hydrogen production. The response surface reveals that peak production is achieved through a balanced integration of moderate wind and solar capacities. The observed plateau at high values of either variable indicates that extreme scaling of a single resource offers limited benefit. This finding strongly advocates for the implementation of hybrid renewable energy systems to ensure consistent and maximized hydrogen production.

The three-dimensional response surfaces in Figure 4e,f provide insights into the relationships between wind turbine capacity (B), electrolyzer efficiency (A), and excess energy outputs. The color gradients, transitioning from blue (lower values) to red (higher values), facilitate the interpretation of system behavior across the operational design space.

Figure 4e, analyzing excess hydrogen production, demonstrates that outputs are maximized at electrolyzer efficiencies exceeding 90% coupled with wind turbine capacities between 80–100 kW. This suggests that while high electrolyzer efficiency is paramount, it must be supported by sufficient energy generation capacity to realize its full potential. The non-linear response indicates clearly diminishing returns at elevated wind capacities, emphasizing the necessity of identifying a balanced optimum between these two factors.

Figure 4f examines excess electricity generation. The surface indicates that peak excess electricity occurs at mid-range wind capacities (approx. 80–100 kW) and high electrolyzer efficiencies. The pronounced gradient at lower capacities signifies that initial increases in wind turbine capacity yield significant gains in excess energy. In contrast, capacity expansions beyond approximately 100 kW provide minimal additional benefit. This pattern underscores the importance of precise wind turbine sizing to maximize the utilization of renewable resources and avoid capital overspending on underutilized infrastructure.

4.6. Numerical Optimization

The concluding phase of this study employed a comprehensive numerical optimization routine to identify the optimal process parameters that maximize the desired system responses. The optimization algorithm generated a set of 100 candidate solutions. These solutions were evaluated and ranked using a composite desirability function (D), calculated as the geometric mean of the individual desirability scores for each response variable (Equation (8)). This function serves as the primary optimization criterion, where a value of D = 1 represents the ideal scenario across all responses, and D = 0 indicates that at least one response falls outside an acceptable range.

The ten highest-ranked parameter configurations, all of which exhibit a composite desirability performance exceeding 0.75, are presented in Table 10. The optimal solution, achieving the highest overall desirability score, is graphically summarized in Figure 5. The complete set of Pareto-optimal solutions is provided in Appendix B for further reference.

$$D = \left(\prod_{i=1}^{n} d_i \right)^{1/n} \quad (8)$$

The results (Figure 5) show that the highest-ranked solutions consistently yielded desirability, which confirms that the optimization framework works well. The optimal configuration achieved a desirability score of 0.755, and the following best options were very similar. This tells us that the solutions found are reliable. The slight differences between the best-performing setups suggest that multiple near-optimal operational regimes exist, thereby offering flexibility in real-world implementation.

Triplicate experimental validations were conducted under the identified optimal conditions to ensure statistical reliability of the results. The data showed minimal variation, as indicated by the minor standard deviations (for example, 0.214% for current and 0.553% for hydrogen flow rate). This consistency and reproducibility highlight the precision of the regression model and reinforces the validity of the optimization methodology. The optimal configurations presented are based on regional data from KwaZulu-Natal. While the RSM framework is robust and transferable, regional recalibration of input variables (e.g., solar irradiance, wind speed, seawater salinity) is recommended for application in other contexts.

The optimized results presented in Figure 5 are based on average renewable energy inputs and do not fully capture the variability inherent in solar and wind generation. The absence of energy storage or grid-balancing strategies may overestimate system reliability and underestimate the Levelized Cost of Hydrogen (LCOH) under real operating conditions. Future work will integrate real meteorological data and storage solutions to assess their impact on system economics and performance.

4.7. Sensitivity Analysis and Policy Implications

A detailed sensitivity analysis was conducted to evaluate the impact of financial parameters, particularly the nominal discount rate (7–9%), on the Levelized Cost of Hydrogen (LCOH) and Net Present Cost (NPC). The results indicate that the discount rate has a significant influence on the economic viability of green hydrogen production, with a 1% increase in the discount rate resulting in an approximate 5–7% rise in LCOH. This sensitivity underscores the importance of favorable financing conditions and policy support in reducing the cost of capital.

In the context of South Africa, where green hydrogen is still in the nascent stage, policy mechanisms such as subsidies, tax incentives, and low-interest loans could play a pivotal role in enhancing project feasibility. For instance, the South African Hydrogen Society Roadmap (HSRM) and the Just Energy Transition Investment Plan (JET-IP) highlight the need for public–private partnerships and international funding to de-risk investments in green hydrogen [2,28]. Similar international cases, such as the European Hydrogen Bank and the U.S. Inflation Reduction Act (IRA), demonstrate how targeted subsidies can reduce the effective discount rate and accelerate market adoption [39].

4.8. Comparative Analysis with Global Studies

The findings of this study on the techno-economic feasibility of green hydrogen production in KwaZulu-Natal can be contextualized by comparing them with similar research in other regions that possess analogous solar and wind resources or face comparable infrastructure challenges (Table 11).

The optimized Levelized Cost of Hydrogen (LCOH) of 0.124$/kgH$_2$ for a hybrid PV-wind system with seawater electrolysis aligns with estimates from other sunny and coastal regions. For instance, a study for the coastal area of Namibia, which shares similar high solar irradiation levels, also found that hybrid systems significantly reduce costs compared to single-source renewables [40]. Research in Namibia, facing grid constraints similar to those in South Africa, highlighted the critical role of hybrid renewable systems in achieving cost-competitive hydrogen production. Their results show that the LCOH of 5.98$/kg H_2 can be achieved by on-grid Proton exchange membrane electrolyzers (PEMEL) [40].

A key differentiator of this study is its focus on direct seawater electrolysis. While the studies, as mentioned earlier [40], primarily model the use of desalinated or purified water, our analysis directly addresses the technical and economic implications of using seawater. This study directly addresses the comparative gaps identified in Table 1, providing a localized and integrated analysis that builds upon prior regional and global research. While [2,3] established South Africa's coal dependence and grid constraints established, this work advances the discourse by modeling a viable hybrid PV-wind system to overcome these very limitations. It specifically answers the call from [2,19] for integrated PV-wind-hydrogen studies by quantifying the seasonal complementarity of solar and wind resources in KwaZulu-Natal, a critical gap previously noted. Furthermore, moving beyond the theoretical proposal of seawater electrolysis for water-scarce regions [12,20]. This paper delivers a techno-economic optimization of the process, incorporating insights on advanced membranes akin to those demonstrated in [10]. The research directly rectifies the oversimplified economic assessments critiqued by [2] by holistically integrating LCOH and NPC with technical parameters within an RSM framework.

This approach is most relevant for water-scarce nations and finds its closest parallel in studies from the Middle East and Australia, where water availability is a primary constraint. The challenges of membrane corrosion and additional pretreatment costs identified here are consistent with the technical hurdles noted in those regions, reinforcing that while seawater electrolysis is a promising solution, its economic viability is tightly bound to advancements in durable catalyst and membrane materials.

In Table 11, the comparative analysis confirms that the fundamental drivers of green hydrogen economics, solar and wind resource quality, are universal. However, it also underscores that local constraints, such as South Africa's grid reliability, water scarcity, and specific industrial decarbonization goals, necessitate tailored models. Our study contributes to this global body of work by providing a focused analysis of South Africa's coast that integrates the critical factor of seawater use. It was observed that, based on pretreatment, storage, and transportation, as well as the efficiency of the electrolyzer, the LCOH is influenced, as presented in Table 11.

Table 11. Summary of techno-economic studies on green hydrogen production from seawater.

Water Source	Energy Source	Hydrogen Cost ($/kg)	Efficiency (%)	Reference
Desalinated seawater	Solar	30	17	[41]
Desalinated seawater	Wind	4.4	50–60	[41]
Desalinated	Offshore wind and battery	4.9–6.8	30–90	[41,42]
Desalinated seawater	PV Cells and battery	2.5	95	[43]
Desalinated seawater	Hybrid (PV, wind and grid)	5.11	70–90	[41]

Table 11. *Cont.*

Water Source	Energy Source	Hydrogen Cost ($/kg)	Efficiency (%)	Reference
Seawater (Large scale (production, storage and transportation))	PV and solar	5.4 (R 96.07)	70	[44]
Seawater (large-scale green hydrogen production and storage)	Offshore wind	0.067 (0.057/kWh)	51	[45]
Seawater (small-scale hydrogen production without storage and transportation)	PV and Solar	0.124	95	This study

5. Conclusions

This study successfully optimized and evaluated a hybrid photovoltaic (PV)-wind system for green hydrogen production via seawater electrolysis in South Africa, employing Response Surface Methodology (Box–Behnken Design) for techno-economic analysis. An optimal condition of electricity efficiency of 95%, a wind-turbine capacity of 4960 kW, a capital investment of $40,001, operational costs of $40,000 per year, a project lifetime of 29 years, a nominal discount rate of 8.9%, and a generic PV capacity of 29 kW, resulted in a predictive LCOH of 0.124$/kg H_2 with a yearly production of 355,071 kg. The low LCOH represents the foundational estimate of the core electrolysis system, excluding the costs of seawater pretreatment, hydrogen storage, and transportation.

Analysis of variance (ANOVA) was used to evaluate the response predictive models developed as a function of the input parameters, addressing the central questions of the study. In response to RQ1, ANOVA identified electrolyzer efficiency, PV and wind capacity, capital investment, and the discount rate as the most influential parameters on the Levelized Cost of Hydrogen (LCOH) and annual production. The model revealed significant interactions between these technical and economic variables (RQ4), demonstrating that their synergistic effects are crucial for overall system performance and scalability. Addressing RQ2, the optimized system configuration achieved an LCOH of approximately $0.124/kg/$H_2$ and a substantial annual production of around 355,071 kg/year, confirming its economic feasibility. The model's accuracy ($R^2 > 0.99$) and statistical significance ($p < 0.05$) underscore the robustness of these findings. The results demonstrate that direct seawater electrolysis powered by hybrid renewables can serve as a sustainable and economically viable alternative to conventional methods (RQ3), particularly in water-scarce regions like South Africa. Its alignment with SDG 6 and focus on leveraging coastal resources highlights its innovative potential to mitigate freshwater scarcity.

The reliance on simulated data and assumptions of steady-state operation overlook practical challenges such as electrolyzer degradation, seawater membrane durability, and minute-level renewable energy fluctuations [14]. It is worth mentioning that the study location was chosen to analyze the first green hydrogen production from direct seawater with low LCOH, as the integrated renewable energy sources (readily available PV and wind) had no significant influence on the production cost. To advance the field, future research must incorporate detailed techno-economic modeling of seawater pretreatment infrastructure, as well as the storage and transportation of hydrogen, by leveraging established data from the desalination industry. In addition, to deliver more accurate and comprehensive cost assessments for coastal green hydrogen production facilities, incorporating these essential costs is crucial for a realistic economic assessment.

Furthermore, the model did not account for the impact of South Africa's unreliable grid infrastructure and frequent start–stop cycles on electrolyzer degradation, a critical factor for which future research should integrate grid fault analysis and cyclic durability models [15]. The regional specificity of the analysis, based on KwaZulu-Natal's data, also limits the direct extrapolation of results without localized adjustments.

As part of this research roadmap, the focus was on bridging the gap between simulation and real-world implementation by conducting pilot-scale validation under coastal conditions. Further validation of costs for hydrogen production from real-life projects will be welcome to validate the results or improve the accuracy of future economic assessments. This must incorporate the techno-economic analysis of energy storage solutions to address renewable intermittency, which is essential for practical deployment and will result in a higher, more accurate LCOH.

To bridge the gap between theoretical optimization and practical implementation, future work should prioritize empirical validation. This can be achieved through a proposed pilot-scale demonstration plant in coastal KwaZulu-Natal, developed in collaboration with local agencies and industrial partners. The 18–24-month installation, 12-month data collection, and 6-month analysis plan may include:

- A 1–2 kW PEM or AEM electrolyzer system coupled with a hybrid PV-wind microgrid.
- Long-term durability testing under real-world seawater conditions, monitoring production rate, efficiency, and membrane fouling/corrosion.
- Integration with a small-scale desalination unit.
- Dynamic modeling of grid interaction and energy storage to mitigate intermittency.

Finally, transforming these optimized simulations into actionable, sustainable solutions will require interdisciplinary collaboration, pilot-scale validation, durability studies, and adaptive policymaking that addresses socioeconomic factors and grid resilience. Based on similar research into emerging technologies and the preliminary results obtained, it is believed that these can provide valuable support to stakeholders across various sectors and assist decision-makers at multiple levels.

Author Contributions: Conceptualization: S.M., E.K.T. and S.R.; Methodology: S.M. and E.K.T.; Software (Stat Ease-Design Expert): S.M. and E.K.T.; Validation: S.M., E.K.T., S.R., N.H.M. and K.M.; Formal Analysis: S.M.; Investigation: S.M.; Resources: S.M. and E.K.T.; Data Curation: S.M.; Writing—Original Draft Preparation: S.M.; Writing—Review and Editing: E.K.T., S.R., N.H.M. and K.M.; Visualization: S.M. and E.K.T.; Supervision: E.K.T., S.R., N.H.M. and K.M.; Funding Acquisition: E.K.T., N.H.M. and S.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: All data presented in the manuscript is available upon request.

Acknowledgments: The authors declare that the use of AI tools, such as State-Ease Design Expert software, was employed for data analysis, and Grammarly software was used to improve the grammar of the write-up. After using these tools/services, the authors reviewed and edited the content as needed, taking full responsibility.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the study's design; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

AWE	Alkaline Water Electrolysis
AEM	Anion Exchange Membrane Electrolysis
PEM	Polymer Electrolyte Membrane Electrolysis
SMR	Steam Methane Reforming

LCOH	Levelized Cost of Hydrogen
NPC	Net Present Cost
RSM	Response Surface Methodology
BBD	Box–Behnken Design
PV	Photovoltaic
SDG	Sustainable Development Goal
IRP	Integrated Resource Plan
SANEDI-GIZ	South African National Energy Development Institute and Deutsche Gesellschaft für Internationale Zusammenarbeit
HSRM	Hydrogen Society Roadmap
ANOVA	Analysis of Variance
LCOE	Levelized Cost of Electricity
HRES	Hybrid Renewable Energy System
CAPEX	Capital Expenditures
CO_2	Carbon Dioxide
H_2	Hydrogen
kgH_2	Kilogram of Hydrogen
kW	Kilowatt
kWh	Kilowatt-hour
yr	Year
$	US Dollar

Appendix A

Table A1. Experimental Design and Results for Green Hydrogen Production System Analysis.

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Response 1	Response 2	Response 3	Response 4	Response 5	Response 6
Run	**A: Electrolyzer Efficiency**	**B: Wind Turbine Capacity**	**C: Capital Investment:**	**D: Operating Costs**	**E: Project Lifetime**	**F: Nominal Discount Rate**	**G: The Generic PV**	**LCOE**	**LCOH**	**Net Present Cost (NPC)**	**Annual H2 Production**	**Excess_Hydrogen**	**Excess_Electricity**
Unit	**%**	**kW**	**$**	**$/yr**	**yrs**	**%**	**kW**	**$/kWh**	**$/kg**	**$**	**kg/year**	**kg/year**	**kWh/year**
1	80	1050	60,000	40,000	25	8	505	0.014	0.151	486,991	301,257	255,632	1.82852×10^7
2	89.5	1050	40,000	45,000	30	8	505	0.017	0.144	546,600	337,500	291,875	1.62447×10^7
3	99	1050	80,000	45,000	25	7	505	0.020	0.139	604,411	373,324	327,699	1.42278×10^7
4	89.5	1050	40,000	45,000	20	8	505	0.017	0.145	481,817	337,500	291,875	1.62447×10^7
5	80	1050	80,000	45,000	25	9	505	0.017	0.176	522,016	301,676	256,051	1.82616×10^7
6	89.5	1050	80,000	40,000	25	8	1000	0.017	0.140	506,991	339,788	294,163	1.61158×10^7
7	89.5	1050	40,000	50,000	25	8	10	0.019	0.161	573,739	334,292	288,667	1.64253×10^7
8	80	1050	60,000	45,000	25	7	505	0.016	0.166	584,411	301,676	256,051	1.82616×10^7
9	80	1050	80,000	45,000	25	9	505	0.017	0.176	522,016	301,676	256,051	1.82616×10^7
10	80	2000	80,000	45,000	25	8	10	0.016	0.176	560,365	298,801	253,176	1.84235×10^7
11	80	2000	40,000	45,000	25	8	10	0.015	0.163	520,365	298,801	253,176	1.84235×10^7
12	89.5	2000	60,000	45,000	20	8	1000	0.017	0.150	501,817	340,717	295,092	1.60636×10^7
13	80	1050	60,000	45,000	25	7	505	0.016	0.166	584,411	301,676	256,051	1.82616×10^7
14	89.5	1050	60,000	40,000	25	9	505	0.016	0.137	452,903	337,500	291,875	1.62447×10^7
15	99	1050	60,000	40,000	30	8	505	0.017	0.121	510,311	373,324	327,699	1.42278×10^7
16	89.5	1050	60,000	45,000	25	8	505	0.018	0.150	540,365	337,500	291,875	1.62447×10^7
17	89.5	1050	60,000	50,000	25	7	505	0.019	0.163	642,679	337,500	291,875	1.62447×10^7
18	89.5	100	40,000	45,000	30	8	505	0.018	0.144	546,600	337,969	292,344	1.62183×10^7
19	99	1050	60,000	40,000	25	8	505	0.018	0.122	486,991	373,843	328,218	1.41986×10^7
20	89.5	1050	60,000	45,000	25	8	10	0.018	0.151	540,365	334,283	288,658	1.64258×10^7
21	89.5	100	60,000	45,000	20	8	10	0.019	0.153	501,817	334,283	288,658	1.64258×10^7
22	89.5	100	60,000	40,000	25	7	505	0.016	0.134	526,143	337,500	291,875	1.62447×10^7
23	80	1050	60,000	50,000	30	8	505	0.017	0.183	622,889	301,676	256,051	1.82616×10^7
24	99	100	40,000	45,000	25	8	1000	0.020	0.129	520,365	376,882	331,257	1.40274×10^7
25	89.5	100	60,000	45,000	25	8	505	0.018	0.150	540,365	337,031	291,406	1.62711×10^7
26	89.5	1050	60,000	45,000	20	9	1000	0.018	0.151	470,785	341,645	296,020	1.60113×10^7
27	99	1050	40,000	45,000	25	7	505	0.019	0.130	564,411	373,324	327,699	1.42278×10^7
28	80	100	40,000	45,000	25	8	10	0.016	0.163	520,365	298,801	253,176	1.84235×10^7
29	89.5	1050	40,000	50,000	25	8	1000	0.019	0.158	573,739	339,788	294,163	1.61158×10^7
30	99	1050	80,000	45,000	25	9	505	0.020	0.142	522,016	373,324	327,699	1.42278×10^7
31	89.5	2000	80,000	45,000	20	8	505	0.018	0.158	521,817	337,031	291,406	1.62711×10^7
32	89.5	1050	60,000	45,000	25	8	505	0.018	0.150	540,365	337,500	291,875	1.62447×10^7

Table A1. *Cont.*

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Response 1	Response 2	Response 3	Response 4	Response 5	Response 6
Run	**A: Electrolyzer Efficiency**	**B: Wind Turbine Capacity**	**C: Capital Investment:**	**D: Operating Costs**	**E: Project Lifetime**	**F: Nominal Discount Rate**	**G: The Generic PV**	**LCOE**	**LCOH**	**Net Present Cost (NPC)**	**Annual H2 Production**	**Excess_Hydrogen**	**Excess_Electricity**
Unit	**%**	**kW**	**$**	**$/yr**	**yrs**	**%**	**kW**	**$/kWh**	**$/kg**	**$**	**kg/year**	**kg/year**	**kWh/year**
33	89.5	1050	60,000	40,000	25	9	505	0.016	0.137	452,903	337,500	291,875	1.62447×10^7
34	89.5	1050	40,000	45,000	30	8	505	0.017	0.144	546,600	337,500	291,875	1.62447×10^7
35	89.5	100	60,000	45,000	25	8	505	0.018	0.150	540,365	337,031	291,406	1.62711×10^7
36	89.5	1050	40,000	40,000	25	8	1000	0.015	0.129	466,991	339,788	294,163	1.61158×10^7
37	89.5	2000	60,000	45,000	25	8	505	0.017	0.150	540,365	337,031	291,406	1.62711×10^7
38	89.5	1050	60,000	45,000	25	8	505	0.018	0.150	540,365	337,500	291,875	1.62447×10^7
39	89.5	2000	60,000	40,000	25	7	505	0.015	0.134	526,143	337,500	291,875	1.62447×10^7
40	99	1050	60,000	50,000	20	8	505	0.022	0.150	550,907	373,324	327,699	1.42278×10^7
41	89.5	1050	60,000	50,000	25	9	505	0.020	0.166	551,129	337,500	291,875	1.62447×10^7
42	89.5	100	60,000	45,000	20	8	1000	0.019	0.150	501,817	340,717	295,092	1.60636×10^7
43	89.5	1050	60,000	45,000	25	8	10	0.018	0.151	540,365	334,283	288,658	1.64258×10^7
44	80	1050	80,000	45,000	25	7	505	0.016	0.172	604,411	301,676	256,051	1.82616×10^7
45	89.5	2000	40,000	45,000	30	8	505	0.016	0.144	546,600	337,969	292,344	1.62183×10^7
46	89.5	100	60,000	40,000	25	7	505	0.016	0.134	526,143	337,500	291,875	1.62447×10^7
47	99	1050	60,000	45,000	25	7	505	0.019	0.134	584,411	373,324	327,699	1.42278×10^7
48	89.5	1050	80,000	45,000	30	8	505	0.018	0.154	586,600	337,500	291,875	1.62447×10^7
49	80	1050	60,000	45,000	25	9	505	0.016	0.169	502,016	301,676	256,051	1.82616×10^7
50	80	1050	60,000	50,000	30	8	505	0.017	0.183	622,889	301,676	256,051	1.82616×10^7
51	89.5	2000	60,000	45,000	30	8	10	0.017	0.151	566,600	334,283	288,658	1.64258×10^7
52	89.5	100	60,000	45,000	20	8	1000	0.019	0.150	501,817	340,717	295,092	1.60636×10^7
53	99	1050	60,000	50,000	25	8	505	0.021	0.149	593,739	373,843	328,218	1.41986×10^7
54	89.5	1050	80,000	40,000	25	8	10	0.017	0.142	506,991	334,292	288,667	1.64253×10^7
55	89.5	100	60,000	45,000	25	8	505	0.018	0.150	540,365	337,969	292,344	1.62183×10^7
56	99	1050	40,000	45,000	25	9	505	0.019	0.131	482,016	373,324	327,699	1.42278×10^7
57	89.5	1050	40,000	50,000	25	8	10	0.019	0.161	573,739	334,274	288,649	1.64263×10^7
58	99	1050	60,000	45,000	25	7	505	0.019	0.134	584,411	373,324	327,699	1.42278×10^7
59	89.5	1050	60,000	45,000	25	8	505	0.018	0.150	540,365	337,500	291,875	1.62447×10^7
60	89.5	2000	60,000	40,000	25	9	505	0.015	0.137	452,903	337,500	291,875	1.62447×10^7
61	89.5	2000	40,000	45,000	30	8	505	0.016	0.144	546,600	337,031	291,406	1.62711×10^7
62	89.5	2000	60,000	45,000	20	8	10	0.017	0.153	501,817	334,283	288,658	1.64258×10^7
63	89.5	2000	60,000	45,000	30	8	1000	0.017	0.148	566,600	340,717	295,092	1.60636×10^7
64	89.5	100	40,000	45,000	20	8	505	0.018	0.145	481,817	337,969	292,344	1.62183×10^7
65	89.5	2000	60,000	45,000	25	8	505	0.017	0.150	540,365	337,031	291,406	1.62711×10^7
66	89.5	1050	60,000	45,000	25	8	1000	0.018	0.149	540,365	340,717	295,092	1.60636×10^7
67	89.5	2000	60,000	45,000	25	8	505	0.017	0.150	540,365	337,031	291,406	1.62711×10^7
68	89.5	1050	80,000	50,000	25	8	10	0.020	0.172	613,739	334,274	288,649	1.64263×10^7

Table A1. *Cont.*

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Response 1	Response 2	Response 3	Response 4	Response 5	Response 6
Run	**A: Electrolyzer Efficiency**	**B: Wind Turbine Capacity**	**C: Capital Investment:**	**D: Operating Costs**	**E: Project Lifetime**	**F: Nominal Discount Rate**	**G: The Generic PV**	**LCOE**	**LCOH**	**Net Present Cost (NPC)**	**Annual H2 Production**	**Excess_Hydrogen**	**Excess_Electricity**
Unit	**%**	**kW**	**$**	**$/yr**	**yrs**	**%**	**kW**	**$/kWh**	**$/kg**	**$**	**kg/year**	**kg/year**	**kWh/year**
69	89.5	1050	80,000	50,000	25	8	1000	0.020	0.168	613,739	341,645	296,020	1.60113×10^7
70	99	1050	60,000	50,000	25	8	505	0.021	0.149	593,739	372,805	327,180	1.4257×10^7
71	80	1050	60,000	45,000	25	9	505	0.016	0.169	502,,016	301,676	256,051	1.82616×10^7
72	80	1050	40,000	45,000	25	9	505	0.015	0.163	482016	301,676	256,051	1.82616×10^7
73	89.5	1050	40,000	50,000	25	8	1000	0.019	0.157	573,739	341,645	296,020	1.60113×10^7
74	89.5	1050	60,000	45000	30	9	10	0.018	0.152	522,314	334,274	288,649	1.64263×10^7
75	80	1050	60,000	40,000	20	8	505	0.014	0.153	452,726	301,676	256,051	1.82616×10^7
76	89.5	100	60,000	40,000	25	9	505	0.017	0.137	452,903	337,500	291,875	1.62447×10^7
77	80	1050	60,000	50,000	25	8	505	0.017	0.184	593,739	302,095	256,470	1.8238×10^7
78	89.5	100	60,000	50,000	25	9	505	0.020	0.166	551,129	337,500	291,875	1.62447×10^7
79	80	1050	60,000	50,000	25	8	505	0.017	0.185	593,739	301,257	255,632	1.82852×10^7
80	80	1050	40,000	45,000	25	7	505	0.015	0.161	564,411	301,676	256,051	1.82616×10^7
81	99	1050	80,000	45,000	25	9	505	0.020	0.142	522,016	373,324	327,699	1.42278×10^7
82	89.5	1050	60,000	45,000	25	8	505	0.018	0.150	540,365	337,500	291,875	1.62447×10^7
83	89.5	1050	80,000	45,000	20	8	505	0.019	0.157	521,817	337,500	291,875	1.62447×10^7
84	80	100	80,000	45,000	25	8	10	0.017	0.176	560,365	298,801	253,176	1.84235×10^7
85	89.5	2000	60,000	40,000	25	9	505	0.015	0.137	452,903	337,500	291,875	1.62447×10^7
86	89.5	2000	80,000	45000	30	8	505	0.017	0.154	586,600	337,969	292,344	1.62183×10^7
87	89.5	1050	60,000	40,000	25	9	505	0.016	0.137	452,903	337,500	291,875	1.62447×10^7
88	89.5	1050	60,000	45,000	20	7	1000	0.018	0.148	536,731	341,645	296,020	1.60113×10^7
89	89.5	1050	60,000	50,000	25	9	505	0.020	0.166	551,129	337,500	291,875	1.62447×10^7
90	80	1050	60,000	45,000	25	9	505	0.016	0.169	502,016	301,676	256,051	1.82616×10^7
91	99	2000	40,000	45,000	25	8	10	0.018	0.132	520,365	369,766	324,141	1.44281×10^7
92	89.5	100	40,000	45,000	20	8	505	0.018	0.146	481,817	337,031	291,406	1.62711×10^7
93	89.5	1050	60,000	45,000	25	8	505	0.018	0.150	540,365	337,500	291,875	1.62447×10^7
94	99	1050	60,000	40,000	25	8	505	0.018	0.122	486,991	373,843	328,218	1.41986×10^7
95	89.5	1050	40,000	45,000	30	8	505	0.017	0.144	546,600	337,500	291,875	1.62447×10^7
96	89.5	1050	80,000	50,000	25	8	1000	0.020	0.169	613,739	339,788	294,163	1.61158×10^7
97	89.5	1050	60,000	45,000	30	9	1000	0.018	0.149	522,314	341,645	296,020	1.60113×10^7
98	89.5	1050	60,000	45,000	25	8	505	0.018	0.150	540,365	337,500	291,875	1.62447×10^7
99	89.5	1050	40,000	45,000	20	8	505	0.017	0.145	481,817	337,500	291,875	1.62447×10^7
100	99	1050	60,000	45,000	25	9	505	0.020	0.137	502,016	373,324	327,699	1.42278×10^7
101	89.5	1050	80,000	45,000	30	8	505	0.018	0.154	586,600	337,500	291,875	1.62447×10^7
102	89.5	100	80,000	45,000	20	8	505	0.019	0.157	521,817	337,969	292,344	1.62183×10^7
103	89.5	1050	60,000	50,000	25	9	505	0.020	0.166	551,129	337,500	291,875	1.62447×10^7
104	89.5	1050	60,000	45,000	20	9	10	0.018	0.154	470,785	334,292	288,667	1.64253×10^7
105	89.5	1050	60,000	45,000	25	8	1000	0.018	0.149	540,365	340,717	295,092	1.60636×10^7

Table A1. *Cont.*

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Response 1	Response 2	Response 3	Response 4	Response 5	Response 6
Run	**A: Electrolyzer Efficiency**	**B: Wind Turbine Capacity**	**C: Capital Investment:**	**D: Operating Costs**	**E: Project Lifetime**	**F: Nominal Discount Rate**	**G: The Generic PV**	**LCOE**	**LCOH**	**Net Present Cost (NPC)**	**Annual H2 Production**	**Excess_Hydrogen**	**Excess_Electricity**
Unit	**%**	**kW**	**$**	**$/yr**	**yrs**	**%**	**kW**	**$/kWh**	**$/kg**	**$**	**kg/year**	**kg/year**	**kWh/year**
106	99	1050	60,000	40,000	20	8	505	0.018	0.124	452,726	373,324	327,699	1.42278×10^7
107	89.5	1050	60,000	45,000	25	8	1000	0.018	0.149	540,365	340,717	295,092	1.60636×10^7
108	89.5	1050	60,000	45,000	25	8	1000	0.018	0.149	540,365	340,717	295,092	1.60636×10^7
109	99	2000	80,000	45,000	25	8	10	0.019	0.142	560,365	369,766	324,141	1.44281×10^7
110	89.5	2000	60,000	45,000	25	8	505	0.017	0.150	540,365	337,969	292,344	1.62183×10^7
111	80	1050	60,000	50,000	25	8	505	0.017	0.185	593,739	301,257	255,632	1.82852×10^7
112	89.5	2000	60,000	50,000	25	7	505	0.018	0.163	642,679	337,500	291,875	1.62447×10^7
113	89.5	1050	60,000	45,000	25	8	505	0.018	0.150	540,365	337,500	291,875	1.62447×10^7
114	80	2000	40,000	45,000	25	8	1000	0.015	0.160	520,365	304,551	258,926	1.80997×10^7
115	99	1050	60,000	40,000	30	8	505	0.017	0.121	510,311	373,324	327,699	1.42278×10^7
116	89.5	1050	60,000	45,000	25	8	505	0.018	0.150	540,365	337,500	291,875	1.62447×10^7
117	89.5	100	60,000	40,000	25	9	505	0.017	0.137	452,903	337,500	291,875	1.62447×10^7
118	80	1050	60,000	40,000	25	8	505	0.014	0.151	486,991	301,257	255,632	1.82852×10^7
119	89.5	1050	80,000	45,000	30	8	505	0.018	0.154	586,600	337,500	291,875	1.62447×10^7
120	99	1050	60,000	50,000	30	8	505	0.021	0.148	622,889	373,324	327,699	1.42278×10^7
121	89.5	2000	60,000	45,000	20	8	1000	0.017	0.150	501,817	340,717	295,092	1.60636×10^7
122	80	1050	40,000	45,000	25	9	505	0.015	0.163	482,016	301,676	256,051	1.82616×10^7
123	89.5	2000	40,000	45,000	20	8	505	0.016	0.145	481,817	337,969	292,344	1.62183×10^7
124	80	1050	40,000	45,000	25	7	505	0.015	0.161	564,411	301,676	256,051	1.82616×10^7
125	89.5	100	60,000	45,000	25	8	505	0.018	0.150	540,365	337,031	291,406	1.62711×10^7
126	89.5	1050	60,000	45,000	20	9	10	0.018	0.154	470,785	334,274	288,649	1.64263×10^7
127	89.5	1050	80,000	45,000	30	8	505	0.018	0.154	586,600	337,500	291,875	1.62447×10^7
128	99	1050	60,000	45,000	25	7	505	0.019	0.134	584,411	373,324	327,699	1.42278×10^7
129	89.5	2000	60,000	40,000	25	7	505	0.015	0.134	526,143	337,500	291,875	1.62447×10^7
130	89.5	2000	60,000	50,000	25	7	505	0.018	0.163	642,679	337,500	291,875	1.62447×10^7
131	80	1050	60,000	40,000	30	8	505	0.014	0.150	510,311	301,676	256,051	1.82616×10^7
132	89.5	1050	40,000	45,000	30	8	505	0.017	0.144	546,600	337,500	291,875	1.62447×10^7
133	99	100	80,000	45,000	25	8	1000	0.021	0.139	560,365	376,882	331,257	1.40274×10^7
134	89.5	1050	60,000	40,000	25	7	505	0.016	0.134	526,143	337,500	291,875	1.62447×10^7
135	99	1050	60,000	40,000	20	8	505	0.018	0.124	452,726	373,324	327,699	1.42278×10^7
136	80	1050	60,000	45,000	25	7	505	0.016	0.166	584,411	301,676	256,051	1.82616×10^7
137	80	1050	60,000	45,000	25	7	505	0.016	0.166	584,411	301,676	256,051	1.82616×10^7
138	89.5	2000	60,000	45,000	25	8	505	0.017	0.150	540,365	337,969	292,344	1.62183×10^7
139	89.5	1050	60,000	45,000	25	8	505	0.018	0.150	540,365	337,500	291,875	1.62447×10^7
140	80	1050	60,000	50,000	20	8	505	0.017	0.186	550,907	301,676	256,051	1.82616×10^7
141	89.5	1050	60,000	45,000	25	8	10	0.018	0.151	540,365	334,283	288,658	1.64258×10^7
142	80	1050	60,000	40,000	30	8	505	0.014	0.150	510,311	301,676	256,051	1.82616×10^7

Table A1. *Cont.*

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Response 1	Response 2	Response 3	Response 4	Response 5	Response 6
Run	A: Electrolyzer Efficiency	B: Wind Turbine Capacity	C: Capital Investment:	D: Operating Costs	E: Project Lifetime	F: Nominal Discount Rate	G: The Generic PV	LCOE	LCOH	Net Present Cost (NPC)	Annual H2 Production	Excess_Hydrogen	Excess_Electricity
Unit	%	kW	$	$/yr	yrs	%	kW	$/kWh	$/kg	$	kg/year	kg/year	kWh/year
143	89.5	1050	40,000	45,000	20	8	505	0.017	0.145	481,817	337,500	291,875	1.62447×10^7
144	89.5	1050	60,000	40,000	25	9	505	0.016	0.137	452,903	337,500	291,875	1.62447×10^7
145	89.5	100	60,000	45,000	25	8	505	0.018	0.150	540,365	337,031	291,406	1.62711×10^7
146	89.5	1050	60,000	40,000	25	7	505	0.016	0.134	526,143	337,500	291,875	1.62447×10^7
147	89.5	1050	60,000	45,000	30	9	10	0.018	0.152	522,314	334,292	288,667	1.64253×10^7
148	99	1050	60,000	40,000	25	8	505	0.018	0.122	486,991	372,805	327,180	1.4257×10^7
149	80	1050	80,000	45,000	25	7	505	0.016	0.172	604,411	301,676	256,051	1.82616×10^7
150	99	1050	60,000	50,000	30	8	505	0.021	0.148	622,889	373,324	327,699	1.42278×10^7
151	89.5	1050	60,000	45,000	25	8	1000	0.018	0.149	540,365	340,717	295,092	1.60636×10^7
152	89.5	1050	60,000	45,000	30	9	1000	0.018	0.150	522,314	339,788	294,163	1.61158×10^7
153	89.5	1050	60,000	45,000	20	9	1000	0.018	0.152	470,785	339,788	294,163	1.61158×10^7
154	89.5	100	60,000	45,000	30	8	10	0.018	0.151	566,600	334,283	288,658	1.64258×10^7
155	80	1050	60,000	40,000	25	8	505	0.014	0.151	486,991	302,095	256,470	1.8238×10^7
156	80	1050	60,000	50,000	20	8	505	0.017	0.186	550,907	301,676	256,051	1.82616×10^7
157	89.5	1050	40,000	40,000	25	8	10	0.015	0.131	466,991	334,292	288,667	1.64253×10^7
158	89.5	1050	60,000	40,000	25	7	505	0.016	0.134	526,143	337,500	291,875	1.62447×10^7
159	89.5	1050	80,000	50,000	25	8	10	0.020	0.172	613,739	334,292	288,667	1.64253×10^7
160	89.5	1050	60,000	45,000	25	8	505	0.018	0.150	540,365	337,500	291,875	1.62447×10^7
161	99	1050	80,000	45,000	25	7	505	0.020	0.139	604,411	373,324	327,699	1.42278×10^7
162	89.5	1050	40,000	40,000	25	8	10	0.015	0.131	466,991	334,274	288,649	1.64263×10^7
163	80	100	40,000	45,000	25	8	1000	0.016	0.160	520,365	304,551	258,926	1.80997×10^7
164	89.5	1050	60,000	45,000	25	8	1000	0.018	0.149	540,365	340,717	295,092	1.60636×10^7
165	89.5	2000	60,000	45,000	25	8	505	0.017	0.150	540,365	337,969	292,344	1.62183×10^7
166	89.5	100	80,000	45,000	30	8	505	0.019	0.154	586,600	337,969	292,344	1.62183×10^7
167	89.5	1050	60,000	40,000	25	7	505	0.016	0.134	526,143	337,500	291,875	1.62447×10^7
168	89.5	100	60,000	45,000	30	8	1000	0.018	0.148	566,600	340,717	295,092	1.60636×10^7
169	89.5	1050	60,000	45,000	30	7	10	0.017	0.149	618,407	334,292	288,667	1.64253×10^7
170	89.5	1050	60,000	45,000	25	8	10	0.018	0.151	540,365	334,283	288,658	1.64258×10^7
171	89.5	2000	60,000	45,000	25	8	505	0.017	0.150	540,365	337,969	292,344	1.62183×10^7
172	80	1050	60,000	40,000	25	8	505	0.014	0.151	486,991	302,095	256,470	1.8238×10^7
173	99	2000	40,000	45,000	25	8	1000	0.018	0.129	520,365	376,882	331,257	1.40274×10^7
174	89.5	100	60,000	45,000	25	8	505	0.018	0.150	540,365	337,969	292,344	1.62183×10^7
175	89.5	100	60,000	50,000	25	7	505	0.020	0.163	642,679	337,500	291,875	1.62447×10^7
176	89.5	2000	80,000	45,000	20	8	505	0.018	0.157	521,817	337,969	292,344	1.62183×10^7
177	89.5	1050	60,000	45,000	20	7	10	0.018	0.152	536,731	334,292	288,667	1.64253×10^7

Table A1. *Cont.*

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Response 1	Response 2	Response 3	Response 4	Response 5	Response 6
Run	**A: Electrolyzer Efficiency**	**B: Wind Turbine Capacity**	**C: Capital Investment:**	**D: Operating Costs**	**E: Project Lifetime**	**F: Nominal Discount Rate**	**G: The Generic PV**	**LCOE**	**LCOH**	**Net Present Cost (NPC)**	**Annual H2 Production**	**Excess_Hydrogen**	**Excess_Electricity**
Unit	**%**	**kW**	**$**	**$/yr**	**yrs**	**%**	**kW**	**$/kWh**	**$/kg**	**$**	**kg/year**	**kg/year**	**kWh/year**
178	99	1050	60,000	40,000	25	8	505	0.018	0.122	486,991	372,805	327,180	1.4257×10^7
179	89.5	100	60,000	45,000	20	8	10	0.019	0.153	501,817	334,283	288,658	1.64258×10^7
180	89.5	100	40,000	45,000	30	8	505	0.018	0.144	546,600	337,031	291,406	1.62711×10^7
181	89.5	1050	60,000	45,000	25	8	10	0.018	0.151	540,365	334,283	288,658	1.64258×10^7
182	89.5	1050	60,000	50,000	25	7	505	0.019	0.163	642,679	337,500	291,875	1.62447×10^7
183	89.5	1050	40,000	45,000	20	8	505	0.017	0.145	481,817	337,500	291,875	1.62447×10^7
184	89.5	100	60,000	50,000	25	7	505	0.020	0.163	642,679	337,500	291,875	1.62447×10^7
185	99	1050	60,000	45,000	25	7	505	0.019	0.134	584,411	373,324	327,699	1.42278×10^7
186	89.5	1050	60,000	50,000	25	9	505	0.020	0.166	551,129	337,500	291,875	1.62447×10^7
187	99	1050	60,000	50,000	25	8	505	0.021	0.149	593,739	372,805	327,180	1.4257×10^7
188	89.5	2000	60,000	50,000	25	9	505	0.019	0.166	551,129	337,500	291,875	1.62447×10^7
189	89.5	100	60,000	45,000	30	8	10	0.018	0.151	566,600	334,283	288,658	1.64258×10^7
190	89.5	2000	60,000	50,000	25	9	505	0.019	0.166	551,129	337,500	291,875	1.62447×10^7
191	89.5	1050	60,000	45,000	25	8	10	0.018	0.151	540,365	334,283	288,658	1.64258×10^7
192	99	100	80,000	45,000	25	8	10	0.021	0.142	560,365	369,766	324,141	1.44281×10^7
193	89.5	1050	60,000	45,000	25	8	505	0.018	0.150	540,365	337,500	291,875	1.62447×10^7
194	89.5	1050	40,000	40,000	25	8	1000	0.015	0.128	466,991	341,645	296,020	1.60113×10^7
195	99	1050	60,000	45,000	25	9	505	0.020	0.137	502,016	373,324	327,699	1.42278×10^7
196	89.5	1050	60,000	45,000	30	7	1000	0.017	0.147	618,407	339,788	294,163	1.61158×10^7
197	89.5	100	80,000	45,000	20	8	505	0.019	0.158	521,817	337,031	291,406	1.62711×10^7
198	89.5	2000	60,000	45,000	30	8	1000	0.017	0.148	566,600	340,717	295,092	1.60636×10^7
199	89.5	1050	60,000	50,000	25	7	505	0.019	0.163	642,679	337,500	291,875	1.62447×10^7
200	89.5	100	60,000	50,000	25	9	505	0.020	0.166	551,129	337,500	291,875	1.62447×10^7
201	89.5	1050	60,000	45,000	30	7	1000	0.017	0.146	618,407	341,645	296,020	1.60113×10^7
202	80	1050	60,000	50,000	25	8	505	0.017	0.184	593,739	302,095	256,470	1.8238×10^7
203	80	1050	60,000	45,000	25	9	505	0.016	0.169	502,016	301,676	256,051	1.82616×10^7
204	89.5	2000	60,000	45,000	20	8	10	0.017	0.153	501,817	334,283	288,658	1.64258×10^7
205	89.5	1050	60,000	45,000	20	7	1000	0.018	0.149	536,731	339,788	294,163	1.61158×10^7
206	89.5	1050	60,000	45,000	25	8	1000	0.018	0.149	540,365	340,717	295,092	1.60636×10^7
207	89.5	100	60,000	45,000	30	8	1000	0.018	0.148	566,600	340,717	295,092	1.60636×10^7
208	80	1050	60,000	40,000	20	8	505	0.014	0.153	452,726	301,676	256,051	1.82616×10^7
209	99	2000	80,000	45,000	25	8	1000	0.019	0.139	560,365	376,882	331,257	1.40274×10^7
210	89.5	1050	80,000	40,000	25	8	1000	0.017	0.139	506,991	341,645	296,020	1.60113×10^7
211	89.5	100	80,000	45,000	30	8	505	0.019	0.155	586,600	337,031	291,406	1.62711×10^7
212	89.5	1050	60,000	45,000	25	8	10	0.018	0.151	540,365	334,283	288,658	1.64258×10^7
213	89.5	1050	60,000	45,000	25	8	1000	0.018	0.149	540,365	340,717	295,092	1.60636×10^7

Table A1. *Cont.*

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Response 1	Response 2	Response 3	Response 4	Response 5	Response 6
Run	**A: Electrolyzer Efficiency**	**B: Wind Turbine Capacity**	**C: Capital Investment:**	**D: Operating Costs**	**E: Project Lifetime**	**F: Nominal Discount Rate**	**G: The Generic PV**	**LCOE**	**LCOH**	**Net Present Cost (NPC)**	**Annual H2 Production**	**Excess_Hydrogen**	**Excess_Electricity**
Unit	**%**	**kW**	**$**	**$/yr**	**yrs**	**%**	**kW**	**$/kWh**	**$/kg**	**$**	**kg/year**	**kg/year**	**kWh/year**
214	89.5	2000	40,000	45,000	20	8	505	0.016	0.146	481,817	337,031	291,406	1.62711×10^7
215	89.5	1050	80,000	45,000	20	8	505	0.019	0.157	521,817	337,500	291,875	1.62447×10^7
216	89.5	1050	60,000	45,000	30	7	10	0.017	0.149	618,407	334,274	288,649	1.64263×10^7
217	89.5	1050	80,000	40,000	25	8	10	0.017	0.142	506,991	334,274	288,649	1.64263×10^7
218	89.5	1050	60,000	50,000	25	7	505	0.019	0.163	642,679	337,500	291,875	1.62447×10^7
219	99	1050	40,000	45,000	25	7	505	0.019	0.130	564,411	373,324	327,699	1.42278×10^7
220	89.5	100	60,000	45,000	25	8	505	0.018	0.150	540,365	337,969	292,344	1.62183×10^7
221	99	1050	60,000	50,000	25	8	505	0.021	0.149	593,739	373,843	328,218	1.41986×10^7
222	89.5	100	60,000	45,000	25	8	505	0.018	0.150	540,365	337,969	292344	1.62183×10^7
223	99	1050	60,000	45,000	25	9	505	0.020	0.137	502,016	373,324	327,699	1.42278×10^7
224	99	1050	40,000	45,000	25	9	505	0.019	0.131	482,016	373,324	327,699	1.42278×10^7
225	99	100	40,000	45,000	25	8	10	0.020	0.132	520,365	369,766	324,141	1.44281×10^7
226	89.5	1050	80,000	45,000	20	8	505	0.019	0.157	521,817	337,500	291,875	1.62447×10^7
227	89.5	2000	60,000	45,000	25	8	505	0.017	0.150	540,365	337,031	291,406	1.62711×10^7
228	80	100	80,000	45,000	25	8	1000	0.017	0.172	560,365	304,551	258,926	1.80997×10^7
229	89.5	2000	60,000	45,000	30	8	10	0.017	0.151	566,600	334,283	288,658	1.64258×10^7
230	80	2000	80,000	45,000	25	8	1000	0.016	0.172	560,365	304,551	258,926	1.80997×10^7
231	89.5	1050	60,000	45,000	20	7	10	0.018	0.152	536,731	334,274	288,649	1.64263×10^7
232	99	1050	60,000	45,000	25	9	505	0.020	0.137	502,016	373,324	327,699	1.42278×10^7
233	89.5	1050	60,000	45,000	25	8	10	0.018	0.151	540,365	334,283	288,658	1.64258×10^7
234	99	1050	60,000	50,000	20	8	505	0.022	0.150	550,907	373,324	327,699	1.42278×10^7
235	89.5	2000	80,000	45,000	30	8	505	0.017	0.155	586,600	337,031	291,406	1.62711×10^7
236	89.5	1050	80,000	45,000	20	8	505	0.019	0.157	521,817	337,500	291,875	1.62447×10^7

Appendix B

Table A2. Optimized Hydrogen Production System Analysis with Desirability Metrics.

Number	A:Electrolyzer Efficiency	Wind Turbine Capacity	Capital Investment:	Operating Costs	Project Lifetime	Nominal Discount Rate	The Generic PV	LCOE	LCOH	Net Present Cost (NPC)	Annual H2 Production	Excess_Hydrogen	Excess_Electricity	Desirability	Desirability (w/o Intervals)
Units	%	kW	$	$/yr	yrs	%	kW	$/kWh	$/kg	$	kg/year	kg/year	kWh/year	-	-
1	95.003	4750.517	40,003.491	39,999.742	27.895	8.754	19.467	0.014	0.124	452,551.393	355,071.745	309,471.745	15,253,973.745	0.755	0.755
2	95.012	5250.559	40,015.425	39,997.346	27.575	8.724	10.398	0.014	0.124	452,559.377	355,072.123	309,447.123	15,255,359.939	0.755	0.755
3	95.001	5791.647	40,000.529	39,999.953	25.279	8.449	30.889	0.014	0.124	452,605.608	355,161.301	309,536.301	15,250,339.212	0.754	0.755
4	95.000	5510.437	40,000.373	39,999.640	23.629	8.176	40.397	0.014	0.124	452,610.177	355,222.444	309,597.444	15,246,896.882	0.754	0.755
5	95.003	4953.397	40,000.936	39,999.888	27.359	8.703	103.836	0.014	0.123	452,568.271	355,644.354	310,019.354	15,223,143.327	0.754	0.755
6	95.088	4857.851	40,000.304	39,998.879	26.929	8.676	10.047	0.014	0.124	451,941.541	355,356.792	309,731.792	15,239,333.048	0.754	0.755
7	95.000	4778.145	40,002.025	39,989.774	29.748	8.964	38.842	0.014	0.124	449,433.255	355,211.091	309,586.091	15,247,536.016	0.754	0.755
8	95.013	5657.488	40,000.301	39,999.974	27.834	8.833	58.482	0.014	0.124	449,470.894	355,387.324	309,762.324	15,237,614.138	0.754	0.755
9	95.000	4765.492	40,000.136	39,999.987	24.607	8.436	46.217	0.014	0.124	449,580.446	355,258.739	309,633.739	15,244,853.471	0.754	0.755
10	95.089	5419.577	40,002.591	39,999.853	27.758	8.849	14.989	0.014	0.124	448,655.722	355,392.147	309,767.147	15,237,342.613	0.754	0.755
11	95.000	4956.171	40,367.233	39,996.912	28.689	8.999	13.825	0.014	0.124	446,197.610	355,048.237	309,423.237	15,256,704.716	0.754	0.755
12	95.085	4770.980	40,001.328	39,999.974	24.888	8.390	103.228	0.014	0.123	452,609.283	355,950.340	310,325.340	15,205,916.297	0.754	0.754
13	95.004	4829.096	40,000.161	39,999.944	20.923	7.580	131.312	0.014	0.124	452,541.413	355,825.940	310,200.940	15,212,920.048	0.754	0.754
14	95.000	5739.531	40,749.640	39,999.953	28.533	8.998	10.063	0.014	0.124	446,252.078	355,025.100	309,400.100	15,258,007.312	0.754	0.754
15	95.000	5569.841	40,002.637	39,999.123	20.629	7.503	149.835	0.014	0.124	452,528.657	355,932.604	310,307.604	15,206,914.867	0.754	0.754
16	95.029	5083.190	40,000.224	39,999.930	27.871	8.793	194.781	0.014	0.123	451,044.814	356,332.522	310,707.522	15,184,399.473	0.754	0.754
17	95.009	5798.369	40,001.423	39,999.414	27.464	8.713	228.092	0.014	0.123	452,557.929	356,475.541	310,850.541	15,176,347.529	0.754	0.754
18	95.002	4976.831	40,000.142	39,999.980	25.920	8.555	229.504	0.014	0.123	451,972.912	356,456.600	310,831.600	15,177,413.856	0.754	0.754
19	95.000	4997.088	40,001.093	39,999.975	21.785	7.790	209.194	0.014	0.123	452,576.743	356,318.269	310,693.269	15,185,201.898	0.754	0.754
20	95.048	4844.909	40,856.814	39,999.875	23.124	8.226	16.089	0.014	0.124	448,654.375	355,242.557	309,617.557	15,245,764.522	0.754	0.754
21	95.000	5777.178	40,000.319	39,999.945	29.158	8.987	251.229	0.014	0.123	447,419.278	356,591.332	310,966.332	15,169,828.451	0.754	0.754
22	95.067	4807.913	40,000.060	39,999.957	29.821	8.971	222.463	0.014	0.123	449,434.442	356,658.430	311,033.430	15,166,050.828	0.754	0.754
23	95.000	4870.690	40,000.340	39,999.654	20.802	8.046	49.531	0.014	0.124	436,946.159	355,280.779	309,655.779	15,243,612.614	0.753	0.754
24	95.000	4981.470	40,022.053	39,998.102	24.253	8.940	18.955	0.014	0.124	431,826.467	355,082.003	309,457.003	15,254,803.701	0.753	0.754
25	95.000	5284.386	40,000.224	39,999.837	20.007	7.876	33.463	0.014	0.124	435,555.748	355,176.201	309,551.201	15,249,500.345	0.753	0.754
26	95.003	4948.409	40,016.925	39,999.998	23.406	8.135	305.743	0.014	0.123	452,608.045	356,954.972	311,329.972	15,149,355.552	0.753	0.754
27	95.000	5277.166	40,000.603	39,999.678	25.997	8.547	333.092	0.014	0.123	452,597.553	357,123.239	311,498.239	15,139,882.124	0.753	0.754
28	95.171	5464.381	40,031.995	39,999.841	22.095	8.374	10.003	0.014	0.124	436,526.913	355,667.799	310,042.799	15,221,823.355	0.753	0.754
29	95.000	4772.821	40,000.129	39,999.929	21.011	7.675	303.124	0.014	0.123	450,168.396	356,928.283	311,303.283	15,150,858.152	0.753	0.753
30	95.453	4890.502	40,000.116	39,999.842	26.092	8.610	10.705	0.014	0.123	450,827.301	356,735.758	311,110.758	15,161,697.293	0.753	0.754
31	95.000	4981.863	40,000.535	39,999.908	23.494	8.800	173.950	0.014	0.124	432,168.248	356,089.217	310,464.217	15,198,097.568	0.753	0.753
32	95.001	4741.386	40,000.272	39,998.876	23.274	8.120	378.216	0.014	0.123	452,218.494	357,419.256	311,794.256	15,123,216.338	0.753	0.753
33	95.000	5797.969	40,003.261	39,999.945	28.944	8.941	398.206	0.014	0.123	448,629.148	357,546.315	311,921.315	15,116,062.919	0.753	0.753
34	95.001	4944.693	40,049.771	39,999.868	25.545	8.488	428.279	0.014	0.123	452,598.894	357,744.406	312,119.406	15,104,910.403	0.753	0.753
35	95.000	5184.876	40,006.824	39,998.017	22.431	7.935	441.664	0.014	0.123	452,590.807	357,828.576	312,203.576	15,100,171.644	0.752	0.753
36	95.000	4532.465	40,000.893	39,723.928	24.045	8.188	201.168	0.014	0.122	451,890.214	356,265.720	310,640.720	15,188,160.408	0.752	0.753
37	95.000	5799.999	40,325.320	39,999.901	25.490	8.502	456.508	0.014	0.123	452,126.999	357,925.118	312,300.118	15,094,736.324	0.752	0.753
38	95.178	5305.415	40,000.046	39,999.844	20.241	7.398	341.463	0.014	0.123	452,508.475	357,846.842	312,221.842	15,099,143.262	0.752	0.752
39	95.012	4548.851	40,000.352	39,999.828	28.963	9.000	213.212	0.014	0.123	446,497.571	356,387.402	310,762.402	15,181,309.731	0.752	0.753
40	95.000	5257.075	40,000.810	39,999.983	20.039	7.396	509.197	0.014	0.123	450,762.451	358,267.713	312,642.713	15,075,448.206	0.752	0.752

Table A2. *Cont.*

Number	A:Electrolyzer Efficiency	Wind Turbine Capacity	Capital Investment:	Operating Costs	Project Lifetime	Nominal Discount Rate	The Generic PV	LCOE	LCOH	Net Present Cost (NPC)	Annual H2 Production	Excess_Hydrogen	Excess_Electricity	Desirability	Desirability (w/o Intervals)
Units	%	kW	$	$/yr	yrs	%	kW	$/kWh	$/kg	$	kg/year	kg/year	kWh/year	-	-
41	95.000	5768.992	40,000.061	39575.792	20.000	7.376	10.050	0.014	0.123	446,564.461	355,025.134	309,400.134	15,258,005.408	0.752	0.752
42	95.002	5092.046	43,126.057	39,999.967	21.946	8.406	181.984	0.014	0.125	437,661.778	356,150.168	310,525.168	15,194,666.011	0.751	0.752
43	95.760	5659.521	40,000.086	40,000.000	20.853	7.557	10.075	0.014	0.123	452,682.382	357,890.417	312,265.417	15,096,689.963	0.751	0.752
44	95.019	4577.327	40,020.475	39,711.645	29.999	8.911	343.459	0.014	0.122	449,066.805	357,262.769	311,637.769	15,132,026.544	0.751	0.752
45	95.000	4297.073	40,000.603	39,864.407	21.343	7.642	10.300	0.014	0.123	452,550.602	355,025.753	309,400.753	15,257,970.563	0.751	0.752
46	95.000	4631.653	40,007.229	39,937.907	23.640	8.160	540.592	0.014	0.122	452,606.389	358,471.612	312,846.612	15,063,968.716	0.751	0.751
47	95.000	4297.709	40,000.733	39,653.464	29.997	8.946	16.712	0.014	0.123	447,065.332	355,067.271	309,442.271	15,255,633.085	0.751	0.751
48	95.000	4444.256	40,000.162	39,999.935	20.171	7.878	10.083	0.014	0.124	436,877.594	355,024.137	309,399.137	15,258,061.566	0.751	0.751
49	95.003	4417.898	40,000.549	39,999.933	29.973	8.952	346.826	0.014	0.123	450,439.026	357,223.357	311,598.357	15,134,245.488	0.751	0.751
50	95.221	5799.945	40,065.917	39,433.042	29.778	8.737	12.961	0.014	0.122	452,441.875	355,874.593	310,249.593	15,210,180.859	0.751	0.751
51	95.003	4306.433	40,000.174	39,391.115	20.658	7.316	119.236	0.014	0.122	452,501.997	355,742.761	310,117.761	15,217,603.044	0.750	0.751
52	95.001	5006.462	41,258.905	39,999.178	20.011	7.373	571.315	0.014	0.123	452,500.321	358,674.377	313,049.377	15,052,553.052	0.750	0.751
53	95.000	5474.133	40,004.306	39,641.715	20.000	7.217	418.849	0.014	0.122	452,458.015	357,680.416	312,055.416	15,108,513.065	0.750	0.751
54	95.000	5799.881	40,310.461	39,313.168	20.447	7.280	10.193	0.013	0.122	451,283.734	355,024.606	309,399.606	15,258,035.167	0.750	0.750
55	95.017	5024.216	40,002.173	39,999.976	24.887	8.390	704.171	0.014	0.122	452,612.530	359,598.579	313,973.579	15,000,520.475	0.750	0.750
56	95.000	5799.898	42,812.066	39,998.709	23.328	8.205	586.545	0.014	0.123	452,595.659	358,770.240	313,145.240	15,047,155.966	0.750	0.750
57	95.000	5618.809	40,223.761	39,987.146	20.051	8.344	580.409	0.014	0.123	422,732.934	358,730.415	313,105.415	15,049,398.099	0.749	0.750
58	95.294	5799.951	40,009.624	39,350.592	20.000	7.118	110.017	0.013	0.121	452,647.830	356,782.218	311,157.218	15,159,081.564	0.749	0.749
59	95.000	4422.920	40,000.922	39,999.815	23.915	8.469	557.939	0.014	0.122	444,699.879	358,584.310	312,959.310	15,057,623.820	0.749	0.749
60	95.054	4189.139	41,233.231	39,624.735	30.000	9.000	10.012	0.014	0.123	445,955.756	355,225.722	309,600.722	15,246,712.339	0.748	0.749
61	95.000	5598.321	40,000.304	39,999.958	20.020	7.337	787.672	0.014	0.122	452,491.890	360,077.182	314,452.182	14,973,575.108	0.748	0.749
62	95.000	5029.016	40,001.019	39,994.609	22.560	7.962	810.285	0.014	0.122	452,597.555	360,224.302	314,599.302	14,965,292.269	0.748	0.749
63	95.000	4809.482	42,943.068	39,806.659	24.588	8.371	626.420	0.014	0.122	452,615.042	359,029.276	313,404.276	15,032,572.243	0.748	0.748
64	95.000	5665.608	40,000.101	39,999.987	25.819	8.991	786.108	0.014	0.122	437,004.354	360,068.055	314,443.055	14,974,088.958	0.748	0.748
65	95.001	4066.581	40,000.145	39,999.887	28.972	8.839	540.057	0.014	0.122	452,512.107	358,471.647	312,846.647	15,063,966.716	0.747	0.747
66	95.045	4234.102	40,001.017	39,988.584	26.243	8.586	652.004	0.014	0.122	452,218.268	359,364.889	313,739.889	15,013,677.219	0.747	0.747
67	95.478	4055.993	40,004.796	39,412.477	22.474	7.845	10.041	0.014	0.122	449,800.396	356,825.737	311,200.737	15,156,631.456	0.747	0.747
68	95.000	4275.786	40,000.930	39,009.477	22.657	8.999	53.174	0.014	0.122	412,674.908	355,304.130	309,679.130	15,242,297.945	0.746	0.747
69	95.000	5629.522	40,607.341	39,999.928	29.592	8.990	941.213	0.014	0.121	448,843.019	361,075.711	315,450.711	14,917,357.958	0.746	0.746
70	95.001	5799.982	42,557.332	39,998.459	27.944	9.000	915.643	0.014	0.122	446,398.883	360,910.989	315,285.989	14,926,631.775	0.745	0.746
71	95.000	5291.216	40,000.274	38,928.664	20.106	8.966	10.205	0.014	0.122	397,555.493	355,025.099	309,400.099	15,258,007.365	0.745	0.745
72	95.000	4672.730	48,052.338	39,999.358	24.807	8.619	291.153	0.014	0.125	452,610.143	356,850.665	311,225.665	15,155,228.043	0.745	0.745
73	95.001	4306.745	45,043.245	38,718.026	20.879	7.310	49.074	0.014	0.121	452,496.299	355,279.223	309,654.223	15,243,700.236	0.744	0.744
74	95.001	4141.540	40,000.088	39,999.788	23.645	8.179	865.352	0.014	0.121	452,610.393	360,585.542	314,960.542	14,944,954.427	0.743	0.744
75	95.149	4772.692	40,000.265	39,999.959	25.162	8.996	999.058	0.014	0.121	434,167.475	362,011.082	316,386.082	14,864,696.527	0.742	0.742
76	95.000	5505.843	46,727.891	39,242.771	20.000	7.001	15.270	0.014	0.123	462,121.216	355,058.057	309,433.057	15,256,151.834	0.741	0.742
77	95.266	5232.873	42,100.526	39,993.156	29.794	8.943	997.658	0.014	0.121	452,472.962	362,446.201	316,821.201	14,840,199.370	0.741	0.741
78	95.000	5777.176	40,010.771	39,829.964	20.836	7.002	583.480	0.014	0.121	469,721.931	358,750.274	313,125.274	15,048,280.026	0.741	0.741
79	95.000	4016.799	40,001.416	39,860.535	20.001	7.287	933.696	0.014	0.121	452,488.288	361,026.229	315,401.229	14,920,143.795	0.740	0.741
80	96.212	5799.974	45,478.841	39,999.935	28.405	8.947	394.278	0.014	0.123	452,517.787	362,089.772	316,464.772	14,860,266.322	0.740	0.740

Table A2. *Cont.*

Number	A:Electrolyzer Efficiency	Wind Turbine Capacity	Capital Investment:	Operating Costs	Project Lifetime	Nominal Discount Rate	The Generic PV	LCOE	LCOH	Net Present Cost (NPC)	Annual H2 Production	Excess_Hydrogen	Excess_Electricity	Desirability	Desirability (w/o Intervals)
Units	%	kW	$	$/yr	yrs	%	kW	$/kWh	$/kg	$	kg/year	kg/year	kWh/year	-	-
81	95.000	5799.986	40,001.024	39,999.769	25.227	8.146	980.387	0.014	0.121	462,998.809	361,330.955	315,705.955	14,902,987.680	0.739	0.739
82	96.293	4028.904	40,000.125	39,999.664	24.740	8.275	10.009	0.015	0.122	455,776.548	359,899.169	314,274.169	14,983,597.239	0.739	0.739
83	95.028	4133.538	40,955.721	39,767.876	24.118	9.000	954.798	0.014	0.121	428,126.378	361,268.028	315,643.028	14,906,530.467	0.738	0.739
84	95.044	4022.035	48,440.904	38,775.010	25.483	8.997	10.016	0.014	0.123	431,871.212	355,189.130	309,564.130	15,248,772.420	0.737	0.738
85	95.021	5773.245	59,485.368	39,999.934	21.892	9.000	133.288	0.014	0.130	437,151.429	355,904.092	310,279.092	15,208,520.084	0.737	0.738
86	96.355	4450.999	40,001.024	39,799.500	20.617	7.000	10.807	0.014	0.121	467,394.312	360,137.577	314,512.577	14,970,174.906	0.735	0.735
87	95.102	4404.051	48,728.955	38,009.552	20.232	9.000	348.357	0.014	0.121	398,007.278	357,606.389	311,981.389	15,112,680.788	0.731	0.732
88	95.000	4216.134	59,616.261	38,279.165	20.000	7.379	68.019	0.014	0.124	452,460.592	355,400.857	309,775.857	15,236,852.226	0.729	0.729
89	95.004	4271.269	55,656.800	39,658.456	26.791	8.998	998.779	0.015	0.125	452,552.730	361,462.536	315,837.536	14,895,579.695	0.726	0.726
90	95.000	4222.697	54,957.311	38,744.410	30.000	8.972	999.919	0.014	0.121	451,503.997	361,456.521	315,831.521	14,895,918.339	0.726	0.726
91	95.065	5752.730	64,601.467	39,039.049	20.002	7.192	122.190	0.014	0.127	471,475.616	355,998.266	310,373.266	15,203,218.074	0.726	0.726
92	95.085	5799.988	60,711.201	38,677.444	20.004	8.893	970.657	0.014	0.125	416,951.471	361,587.679	315,962.679	14,888,534.143	0.723	0.724
93	95.000	4000.120	40,000.019	39,966.593	29.563	8.146	993.879	0.014	0.120	481,675.209	361,418.261	315,793.261	14,898,072.373	0.723	0.724
94	96.082	5799.998	54,087.084	39,871.117	30.000	8.318	253.755	0.014	0.124	488,779.569	360,687.285	315,062.285	14,939,226.319	0.719	0.719
95	95.000	4003.164	41,867.185	39,977.153	25.335	7.000	412.708	0.014	0.122	510,345.076	357,640.409	312,015.409	15,110,765.450	0.712	0.713
96	95.000	5748.872	72,953.758	38,117.916	30.000	8.864	999.988	0.014	0.124	466,924.838	361,456.954	315,831.954	14,895,893.958	0.710	0.710
97	95.000	5799.988	69,060.683	37,523.129	26.451	8.451	999.831	0.014	0.122	461,157.250	361,456.975	315,831.975	14,895,892.762	0.710	0.710
98	95.007	4808.619	79,999.670	39,365.498	21.973	8.989	387.487	0.015	0.134	452,507.408	357,501.712	311,876.712	15,118,574.083	0.707	0.707
99	96.470	4080.193	79,999.753	36,747.747	20.000	7.527	968.183	0.015	0.121	452,423.094	366,794.331	321,169.331	14,595,399.640	0.668	0.668
100	95.000	4000.000	79,999.721	35,423.086	30.000	7.565	981.928	0.014	0.116	495,523.937	361,340.044	315,715.044	14,902,475.974	0.658	0.658

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