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**The Effect of Electrolyzer Sizing and Renewable Resource
Complementarity on the Levelized Cost of Hydrogen
through Techno-Economic Analysis**

A Thesis submitted in partial satisfaction of the requirements
for the degree of Master of Science

in

Environmental Systems
Energy Systems Engineering

by

Maria Florencia Dotta Brugman

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Professor Samuel Markolf

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To my parents, for giving me the foundation to become who I am; to my brother, for always pushing me to grow; and to my nieces and nephews, for their love and the joy they bring into my life.

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ABSTRACT

Green hydrogen is widely recognized as a promising energy carrier that enables deep decarbonization and integrates variable renewable energy sources. However, its large-scale deployment remains constrained by high production costs and operational challenges associated with intermittent renewable electricity.

This thesis presents an hourly techno-economic analysis of green hydrogen production in off-grid hybrid solar–wind systems directly coupled to electrolyzers, without battery storage or grid interaction. To determine the drivers of cost, the study focuses on the impact of renewable resource complementarity and electrolyzer sizing on hydrogen production cost. An hourly modeling framework (8760 h) was developed to simulate renewable electricity generation, electrolyzer operation, hydrogen production, and the Levelized Cost of Hydrogen (LCOH). Renewable generation profiles are obtained using the System Advisor Model (SAM), while a custom model evaluates electrolyzer performance under operational constraints and variable electrolyzer-to-renewable capacity ratios (R). The framework is applied across a diverse matrix including four representative U.S. locations spanning solar-dominant, wind-dominant, low-resource, and highly complementary resource conditions; five renewable energy configurations ranging from PV-only to wind-only systems with hybrid solar–wind combinations; three electrolyzer technologies (AWE, PEM, and SOEC); and electrolyzer-to-renewable sizing ratios ranging from 0.2 to 1.

The results reveal that LCOH exhibits a convex relationship with R , confirming the existence of an optimal sizing point driven by the trade-off between renewable curtailment and electrolyzer utilization. It was found that the electrolyzer-to-renewable sizing ratio strongly influences electrolyzer capacity factor, curtailed energy, hydrogen production, and overall system economics. Among the evaluated locations, Amarillo–Texas achieves the lowest LCOH (5.61 USD/kg) for a PEM electrolyzer coupled to a hybrid PV45–WD45 configuration, highlighting the benefits of solar–wind complementarity. While hybrid systems generally improve electrolyzer utilization and reduce LCOH in locations with balanced solar-wind resources, while PV-only systems remain optimal in solar-dominant regions such as

Phoenix–Arizona. Among the technologies studied, PEM consistently provides the lowest LCOH among the evaluated electrolyzer technologies.

Sensitivity analyses indicate that renewable energy and electrolyzer capital costs are the dominant drivers of LCOH reduction. Under cumulative cost reduction scenarios, substantial decreases in both renewable and electrolyzer CAPEX are required to approach low-cost hydrogen targets, while renewable resource quality remains a fundamental determinant of system economics.

Overall, the results demonstrate that the economic viability of green hydrogen depends not only on cost reductions, but also on optimal system design, electrolyzer sizing, and renewable resource complementarity. This work highlights the importance of integrated hourly techno-economic modeling for identifying cost-effective renewable hydrogen production under variable renewable energy conditions.

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LIST OF SYMBOLS

$LCOH$	Levelized Cost of Hydrogen [USD/kg]	2
$LCOE$	Levelized Cost of Electricity [USD/kWh]	18
E_{PV}	Annual solar energy generation [kWh/year]	18
E_{Wind}	Annual wind energy generation [kWh/year]	18
E_{mix}	Total annual renewable energy generation [kWh/year] . . .	18
$\eta_{Rectifier}$	Rectifier efficiency[%]	19
$P_{Available}$	Available renewable power [kW]	19
$P_{Electrolyzer,min}$	Minimum electrolyzer operating power [kW]	19
$P_{Electrolyzer,size}$	Electrolyzer rated capacity [kW]	19
$P_{Electrolyzer}$	Electrolyzer power consumption [kW]	19
$E_{Electrolyzer}$	Annual energy consumed by the electrolyzer [kWh/year] . .	21
R	Electrolyzer-to-renewable capacity ratio [-]	22
$P_{Renewable,size}$	Total installed renewable capacity [kW]	22
CF_{El}	Electrolyzer capacity factor [%]	22
m_{H_2}	Annual hydrogen production [kg/year]	22
e_{El}	Specific energy consumption [kWh/kg _{H₂}]	23
m_{H_2O}	Annual water consumption [kg/year]	23
r_{H_2O/H_2}	Specific water consumption [kg/kg _{H₂}]	23
d	Discount rate	23
PL	Project lifetime [years]	23
C_{H_2O}	Annual water cost [USD/year]	24
c_{water}	Water unit cost [USD/kg]	24
H_{stack}	Electrolyzer stack lifetime [hours]	25

Chapter 1

INTRODUCTION

1.1 Background and Motivation

Global energy demand continues to increase due to population growth, economic development, electrification of major sectors, and the rapid expansion of artificial intelligence applications [1]. Despite the accelerated deployment of renewable energy technologies, the global energy system remains heavily dependent on fossil fuels, which are the main source of greenhouse gas (GHG) emissions [2].

At the same time, the declining cost of renewable energy is driving a rapid increase in the penetration of variable resources such as solar and wind. While essential for decarbonization, these technologies are inherently intermittent and weather dependent, leading to mismatches between electricity generation and demand on hourly, daily, and seasonal time scales [3].

As a result, reliable energy storage and flexible energy carriers become critical to ensure system stability and enable deep decarbonization [4]. In this context, hydrogen produced via water electrolysis using renewable electricity (commonly referred to as green hydrogen) offers a pathway for long-term energy storage and for decoupling energy production from consumption in time and space [4, 5]. However, its large-scale deployment remains constrained by economic challenges, highlighting the need for a detailed techno-economic evaluation [6].

1.2 Overview of Green Hydrogen

Hydrogen is a versatile energy carrier that enables energy transport, storage, and conversion across sectors [7]. In energy systems with high shares of renewable generation, green hydrogen can provide operational flexibility by storing surplus electricity and balancing supply and demand over extended time scales.

Despite its potential, deployment remains limited due to high production costs, infrastructure constraints, conversion losses, and uncertain market conditions

[6]. Its economic performance is commonly evaluated using the Levelized Cost of Hydrogen *LCOH*, expressed in (USD/kg), which represents the discounted cost of hydrogen production over the system lifetime. *LCOH* integrates capital and operational costs with hydrogen production, enabling a consistent comparison between technologies and system configurations [8].

The competitiveness of green hydrogen is strongly dependent on renewable energy costs, electrolyzer capital costs, system design, and operational strategies. Current objectives aim to reduce production costs below 2 USD/kg in the near term and approach 1 USD/kg in the longer term, although achieving these goals remains uncertain [9].

1.3 Research objectives

This thesis presents a techno-economic analysis of green hydrogen production in off-grid renewable energy systems, with a primary focus on the Levelized Cost of Hydrogen. The study develops an hourly modeling framework integrating solar and wind generation with electrolyzer operation.

Using location-specific renewable resource data, the model simulates hourly electricity generation and evaluates electrolyzer performance under technical constraints, such as minimum load and capacity limits. Based on these simulations, hydrogen production, electrolyzer utilization, and total system costs are quantified to calculate *LCOH*.

The main objectives of this work are:

- Develop an hourly techno-economic model for off-grid renewable hydrogen production
- Evaluate *LCOH* across different locations and renewable system configurations
- Identify optimal electrolyzer-to-renewable sizing ratios under varying resource conditions
- Determine the key technical and economic drivers influencing *LCOH*

The framework is applied to multiple locations with distinct renewable resource profiles, including solar-dominated, wind-dominated, and hybrid systems. This comparative analysis enables the identification of minimum-cost configurations

and highlights the role of resource complementarity in improving system performance.

Recent research has increasingly explored the techno-economic performance of renewable hydrogen systems using a variety of modeling approaches and system configurations. This study focuses on off-grid systems and explicitly examines the interaction between renewable variability and electrolyzer sizing. By allowing the electrolyzer-to-renewable capacity ratio to vary, this work provides an hourly techno-economic assessment of how system design influences hydrogen production, utilization, and cost performance across diverse resource conditions.

Chapter 2

LITERATURE REVIEW

This chapter reviews the existing literature relevant to framing the research context and defining the technological and economic challenges addressed in this thesis as well as review some LCOH results.

2.1 Global Energy Transition and Climate Targets

Global energy demand continues to grow due to population increase, economic development, electrification, and emerging digital technologies such as artificial intelligence (AI), which is expected to significantly increase electricity consumption [10]. Despite the expansion of renewable energy, fossil fuels remain the dominant energy source and the primary contributor to greenhouse gas (GHG) emissions, driving climate change [2].

International efforts such as the Paris Agreement and COP28 aim to limit global warming below 2°C while pursuing efforts to restrict it to 1.5°C above pre-industrial levels. Achieving these targets requires a rapid transition toward low-carbon energy systems, large-scale renewable deployment, and improved energy efficiency.

The increasing share of variable renewable energy sources, such as wind and solar PV, intensifies the need for system flexibility and energy storage across multiple time scales (daily, weekly, and seasonal) [2]. In this context, green hydrogen is increasingly recognized as a key energy carrier, enabling long-term storage, renewable integration, and the decarbonization of hard-to-abate sectors. In addition, hydrogen has the potential to reshape global energy markets while supporting sustainable economic development [11].

Artificial Intelligence

Artificial intelligence (AI) is emerging as a major driver of electricity demand growth. Data centers supporting AI operations consumed approximately 1.5% of

global electricity in 2024 and could reach between 670 and 1260 TWh by 2030 (depending on the projected scenario) [12]. These facilities require continuous, high-power supply, posing challenges for energy systems that rely on variable renewable sources. In the short term, this demand may increase reliance on dispatchable and carbon-intensive generation [13, 14].

Low-carbon solutions such as nuclear, geothermal, and hydrogen-based systems are being explored to provide reliable supply. In this context, hydrogen can contribute as a long-term and seasonal energy storage option, supporting system flexibility and renewable integration.

2.2 Hydrogen production pathways

Global hydrogen production is approximately 87 million tons per year, with nearly 95% derived from fossil fuels, primarily through steam methane reforming of natural gas, resulting in significant CO₂ emissions. Only a small share of hydrogen is produced from low-emission pathways, including renewable-powered water electrolysis [5].

Hydrogen production pathways are commonly classified based on their carbon intensity and energy source, including gray, blue, turquoise, green, pink, and yellow hydrogen [7]. Among these, green hydrogen—produced via electrolysis using renewable electricity, represents the most promising low-emission pathway as we can see in the list below and in the Figure 2.1 [5, 15].

Hydrogen Production Pathways by Color Classification [7]:

- **Grey:** Produced from fossil fuels (e.g., natural gas or coal), with high CO₂ emissions.
- **Blue:** Fossil-based hydrogen with carbon capture and storage, reducing emissions.
- **Turquoise:** Produced via methane pyrolysis, generating solid carbon instead of CO₂.
- **Green:** Produced by renewable-powered electrolysis, with near-zero emissions.
- **Pink:** Electrolysis powered by nuclear energy.

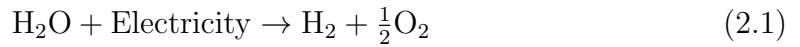
- **Yellow:** Electrolysis using grid electricity, with emissions depending on the grid mix.

	Grey	Blue	Turquoise	Green	Pink	Yellow
Primary Inputs	Natural gas + water, coal + air 	Natural gas+ water+ air 	Natural gas + water 	Renewable electricity + water 	Nuclear electricity+ water 	Grid electricity+ water 
Process	SMR, coal gasification 	SMR + CCS 	Pyrolysis 	Electrolysis 	Electrolysis 	Electrolysis 
Output	H ₂ + CO ₂	H ₂ + CO ₂ (partly captured)	H ₂ + C	H ₂ + O ₂	H ₂ + O ₂ + nuclear waste	H ₂ + CO ₂

Figure 2.1: Hydrogen color classification [7]

Green Hydrogen

Green hydrogen is produced through water electrolysis powered by renewable electricity, splitting water into hydrogen and oxygen as we can see in the following Equation. 2.1:



Under standard conditions (25°C, 1 atm), the theoretical minimum cell voltage required for water splitting is 1.23 V. However, in practical systems, operating voltages typically reach around 1.48 V due to activation overpotential and ohmic losses within the electrolyzer components [5].

Despite its potential, electrolysis currently represents less than 4% of global hydrogen production [15]. However, rapid growth is expected, with installed capacity projected to increase from around 6 GW in 2024 to nearly 470 GW by 2030 [2].

2.3 Electrolyzers

Water electrolysis is an electrochemical process that converts electrical energy into hydrogen by splitting water (H_2O) into hydrogen (H_2) and oxygen (O_2). Electrolyzers transform electrical energy into chemical energy stored in hydrogen molecules [15].

Although the fundamental reaction is common across technologies, electrolyzer systems differ in electrolyte type, operating conditions, and performance characteristics [16]. The main technologies considered in this work are Alkaline Water Electrolysis (AWE), Proton Exchange Membrane (PEM), and Solid Oxide Electrolysis Cells (SOEC), which are classified based on their ionic charge carriers (OH^- , H^+ , O^{2-}) as we can see in Figure 2.2 [15].

Electrolyzer systems consist of an electrochemical stack and balance-of-plant components (e.g., power electronics, water management, gas separation, and cooling). Their operation is subject to technical constraints such as minimum load, efficiency, and capacity limits, which are particularly relevant when coupled with variable renewable energy sources [5].

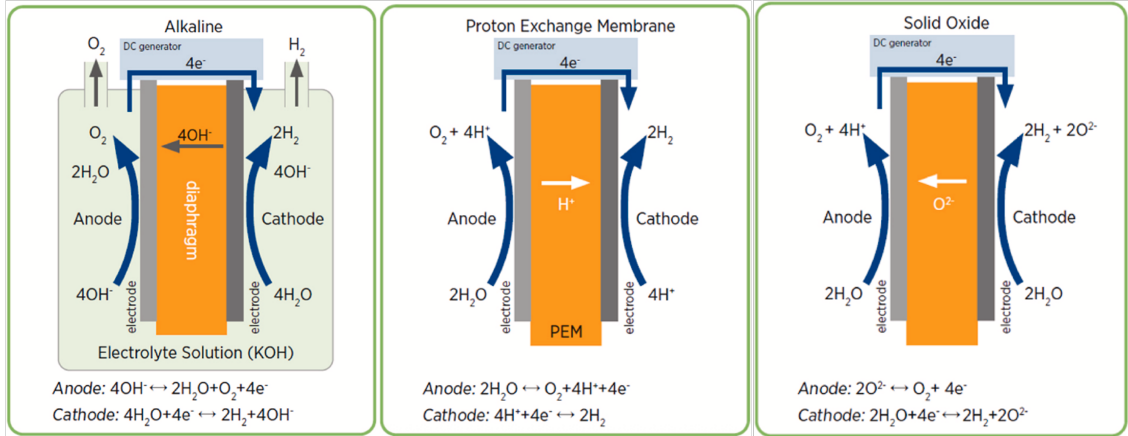


Figure 2.2: Electrolyzer Technologies and Operating Principles [16]

2.3.1 Alkaline Electrolyzers (AWE)

Alkaline electrolyzers use a liquid electrolyte (typically KOH or NaOH) to transport hydroxide ions (OH^-) between electrodes as you can see in Figure 2.2. The electrolyte is usually recirculated through the system, requiring additional balance-of-plant components such as pumps and gas-liquid separation units.

They are the most mature and widely deployed technology, characterized by low cost, simple design, and long lifetime. However, they present limitations in dynamic operation, lower current densities, and challenges such as gas crossover and reduced performance under variable loads [16].

- **Alkaline electrolyzer stack (most common materials) [15]:**

- **Diaphragm:** ZIRFON
- **Electrolyte:** Potassium hydroxide (KOH)
- **Electrode catalysts:** Nickel mesh
- **Bipolar plates:** Nickel-coated stainless steel

2.3.2 Proton Exchange Membrane Electrolyzers (PEM)

PEM electrolyzers use a solid polymer electrolyte membrane, typically perfluorosulfonic acid (PFSA, e.g., Nafion[®]), which conducts protons (H^+) from the anode to the cathode. Water is fed to the anode, where it is oxidized to produce oxygen, protons, and electrons. The protons migrate through the membrane, while electrons travel through the external circuit to the cathode, where hydrogen is formed, as you can see in Figure 2.2. The solid membrane eliminates the need for a liquid electrolyte and enables compact system design. PEM electrolyzers can respond rapidly to changes in power input, making them particularly suitable for integration with intermittent renewable energy sources [16].

PEM systems can also operate at high pressures (up to ~ 70 bar), enabling direct hydrogen compression. However, the acidic environment and high operating potentials require the use of noble metal catalysts (e.g., platinum and iridium) and corrosion-resistant materials such as titanium, significantly increasing system cost. Additionally, PEM electrolyzers are sensitive to water impurities and still face challenges related to long-term durability and large-scale deployment [16].

- **PEM electrolyzer stack (most common materials) [15]:**

- **Proton exchange membrane:** Nafion[®]
- **Electrode catalysts:**
 - * **Anode catalysts:** Iridium oxide (IrO_2)
 - * **Cathode catalyst:** Platinum (Pt)

- **PTL (Porous Transport Layers):**
 - * **Anode:** Titanium (Ti)
 - * **Cathode:** Carbon paper (C), Titanium (Ti)
- **Bipolar plates:**
 - * **Anode:** Titanium (Ti) with platinum coating
 - * **Cathode:** Titanium (Ti) with gold coating

2.3.3 Solid Oxide Electrolyzers (SOEC)

SOEC systems operate at high temperatures (700–850°C) using a solid ceramic electrolyte that conducts oxygen ions (O^{2-}). The elevated temperature improves reaction kinetics and reduces electrical energy requirements, enabling high efficiencies and potential integration with thermal energy sources. In these systems, water is supplied as steam to the cathode, where it is reduced to hydrogen and oxygen ions. The oxygen ions migrate through the electrolyte to the anode, where they form oxygen gas and release electrons, as you can see in Figure 2.2.

However, SOEC technology faces challenges related to material degradation, thermal cycling, and limited operational flexibility [16].

- **SOEC electrolyzer stack (most common materials) [15]:**
 - **Electrolyte:** YSZ (Yttria-Stabilized Zirconia)
 - **Electrode catalysts:**
 - * **Anode (Air/O₂) electrode:** LSC, LSM, LSCF
 - * **Cathode (Fuel) electrode:** Ni + YSZ
 - **Interconnect plate:** Crofer and other high-temperature ferritic stainless steels with protective coating
 - **Seals:** Glass, glass-ceramic, mica

Abbreviations: YSZ (Yttria-Stabilized Zirconia), LSC (Lanthanum Strontium Cobaltite), LSM (Lanthanum Strontium Manganite), LSCF (Lanthanum Strontium Cobalt Ferrite).

2.3.4 Advantages, Disadvantages, and Comparison

Each electrolyzer technology presents trade-offs between cost, efficiency, maturity, and operational flexibility. AWE is the most mature and cost-effective but

less flexible. PEM offers high responsiveness and compact design but at higher cost. SOEC provides the highest efficiency but faces challenges related to durability and high-temperature operation. As we can see in the list below:

- **Alkaline electrolyzers (AWE)** are the most mature and cost-effective option, with long lifetimes and simple system design. However, they have lower current densities, limited dynamic response, and challenges related to gas crossover and operation under variable loads.
- **PEM electrolyzers** offer high efficiency, compact design, and excellent dynamic response, making them well-suited for renewable energy integration and load-following operation. Their main drawbacks are the high cost associated with noble metal catalysts and sensitivity to operating conditions.
- **SOEC systems** provide the highest theoretical efficiency and the ability to utilize thermal energy, as well as additional functionalities such as syngas production. However, their high operating temperature introduces challenges related to durability, system complexity, and limited flexibility.

Overall, no single technology is optimal for all applications. The selection of an electrolyzer depends on system requirements such as scale, energy source variability, cost constraints, and integration with other processes, we can see a comparative Table in 2.1. Ongoing research and development efforts continue to improve performance, reduce costs, and expand the applicability of all technologies [16].

Table 2.1: Electrolyzer Technologies Comparison [15]

Parameter	Alkaline	PEM	Solid Oxide
Operating temperature	70–90°C	50–80°C	700–850°C
Operating pressure	1–30 bar	<70 bar	1 bar
Electrolyte	Potassium hydroxide (KOH) 5–7 mol/L	PFSA membranes	Yttria-stabilized Zirconia (YSZ)
Separator	ZrO ₂ stabilized with PPS mesh	Solid electrolyte	Solid electrolyte
Electrode/catalyst (O ₂ side)	Nickel-coated stainless steel	Iridium oxide	Perovskite-type (LSCF, LSM)
Electrode/catalyst (H ₂ side)	Nickel-coated stainless steel	Pt nanoparticles on carbon	Ni/YSZ
Porous transport layer (anode)	Nickel mesh (optional)	Pt-coated porous titanium	Coarse Ni mesh/foam
Porous transport layer (cathode)	Nickel mesh	Porous titanium or carbon cloth	None
Bipolar plate (anode)	Ni-coated stainless steel	Pt-coated titanium	None
Bipolar plate (cathode)	Ni-coated stainless steel	Au-coated titanium	Co-coated stainless steel
Frames and sealing	PSU, PTFE, EPDM	PTFE, PSU, ETFE	Ceramic glass

Although water electrolysis is a promising low-emission pathway for hydrogen production, its economic competitiveness remains constrained by high electricity consumption and capital costs. Electrolyzer performance, particularly efficiency, minimum load, and operational flexibility, plays a critical role in determining system utilization and overall cost. These factors become especially relevant in systems

powered by variable renewable energy, where the temporal mismatch between generation and demand directly impacts hydrogen production and LCOH. Ongoing research focuses on improving efficiency, durability, and cost reduction through advances in materials and system design, which are essential for enabling large-scale deployment of green hydrogen technologies [15].

In Table 2.2, we can see some of the key actual values and target for 2050.

Table 2.2: Electrolyzer Technologies: Current and Target Performance [16]

Parameter	Actual	Target 2050
Alkaline Water Electrolysis (AWE)		
Nominal current density [A/cm ²]	0.2–0.8	> 2
Voltage range [V]	1.4–3	< 1.7
Operating temperature [°C]	70–90	> 90
Cell pressure [bar]	< 30	> 70
Efficiency [%]	65–70	> 70
Durability	High	–
Water quality	Lower purity acceptable	–
Minimum load [%]	20 [17]	5
Electrical efficiency [kWh/kg H ₂]	50.1 [17]	< 45
Lifetime stack [h]	70,080 [17]	100,000
CAPEX [USD/kW]	1,451 [17]	< 200
OPEX [\$/kW-y]	73 [17]	–
Proton Exchange Membrane (PEM)		
Nominal current density [A/cm ²]	1–2	4–6
Voltage range [V]	1.4–2.5	< 1.7
Operating temperature [°C]	50–80	80
Cell pressure [bar]	< 70	> 70
Efficiency [%]	60–70	> 80
Durability	High	–
Water quality	High-purity required	–
Minimum load [%]	5 [17]	Same
Electrical efficiency [kWh/kg H ₂]	46.7 [17]	< 45
Lifetime stack [h]	52,560 [17]	100,000–120,000
CAPEX [USD/kW]	1,627 [17]	< 200
OPEX [\$/kW-y]	82 [17]	–
Solid Oxide Electrolysis Cells (SOEC)		
Nominal current density [A/cm ²]	0.3–1	> 2
Voltage range [V]	1.0–1.5	< 1.48
Operating temperature [°C]	700–850	< 600
Cell pressure [bar]	~1	> 20
Efficiency [%]	80–90	> 90
Durability	Low to moderate	–
Water quality	High-purity required	–
Minimum load [%]	30 [17]	< 5
Electrical efficiency [kWh/kg H ₂]	41.2 [17]	< 40
Lifetime stack [h]	43,800 [17]	80,000
CAPEX [USD/kW]	3,562 [17]	< 300
OPEX [\$/kW-y]	178 [17]	–

2.4 Review of LCOH calculations

The economic viability of green hydrogen production remains a key challenge, and LCOH is widely used to assess the competitiveness of different production pathways.

Table 2.3 summarizes recent studies on LCOH estimation under diverse system configurations, locations, and modeling approaches. Reported values range from 3.2 to 13.4 USD/kg, reflecting differences in resource availability, system scale, and key assumptions, including the electrolyzer-to-renewable capacity ratio (R).

This variability highlights the sensitivity of LCOH to renewable electricity costs, electrolyzer capital costs, system design, and operational strategies. In particular, the temporal alignment between renewable generation and electrolyzer operation plays a critical role in determining overall system performance and cost.

Table 2.3: Summary of recent studies on green hydrogen production costs.

Year	Energy source	Electrolyzer type	LCOH (USD/kg)	R	Author
2022	Grid	AWE	7.60	1	[18]
		PEM	8.55		
		SOEC	10.16		
2023	Solar, wind	AWE	5.9	0.2	[19]
2023	Solar	Generic	3.2	0.6	[20]
2023	Solar, wind	AWE	7.25	1	[21]
		PEM	13.44		
2024	Wind	PEM	PV: 4.6 WT: 5.6	1	[22]
2024	Solar Wind Onshore(WT-N) Wind Offshore(WT-F)	AWE PEM	AWE-PV: 8.41 PEM-PV: 8.43 AWE-WT-N: 7.02 PEM-WT-N: 7.12 AWE-WT-F: 7.75 PEM-WT-F: 9.69	1	[23]
2024	Solar, wind	PEM	3.7- 4.4	0.5	[24]
2021	Solar	PEM	13.71	–	[25]
	Wind		6.91		

Chapter 3

MODEL DESCRIPTION

This chapter presents the modeling framework used to evaluate green hydrogen production from an off-grid hybrid solar–wind system. The framework integrates renewable generation simulated with the System Advisor Model (SAM) [26] and a custom electrolyzer operational and economic model developed at Thermal and Electrochemical Laboratory (TEEL) and based on Tubalinal works [17].

3.1 Model Architecture and Data Treatment

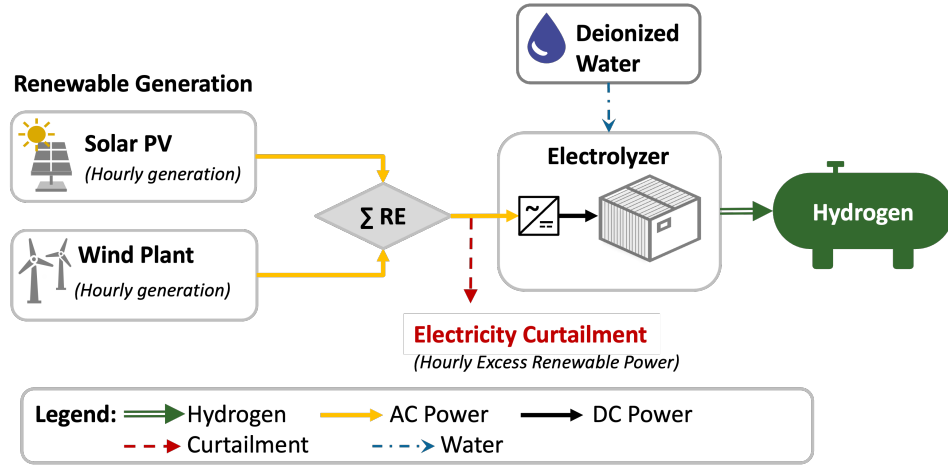


Figure 3.1: System architecture of the off-grid hybrid renewable hydrogen production model

The system consists of an off-grid hybrid solar–wind configuration directly coupled to an electrolyzer, as illustrated in Figure 3.1. Renewable electricity is generated from a solar photovoltaic (PV) array and a wind power plant and is either consumed by the electrolyzer or curtailed. No grid connection or energy storage is considered. Deionized water is supplied as a feedstock for hydrogen production via electrolysis.

Hourly AC power outputs are obtained from SAM for both solar PV and wind systems to ensure consistency when combining renewable sources within hybrid configurations. Since the electrolyzer operates with DC power, a rectifier stage is included between the renewable generation system and the electrolyzer. The detailed AC/DC treatment and rectifier efficiency assumptions are presented in subsequent sections.

This framework extends previous work [17] by incorporating hybrid renewable configurations across multiple locations and introducing a variable electrolyzer-to-renewable capacity ratio. This enables analysis of the interaction between renewable resource variability, system sizing, and electrolyzer operation.

The modeling workflow integrates two main components: a Renewable Energy Model and a Hydrogen Production and Economic Model. Figure 3.2 illustrates the workflow adopted in this study. Hourly power outputs are processed under electrolyzer operational constraints, including minimum load and rated capacity, to determine energy supplied to the electrolyzer, curtailed energy, and electrolyzer operating hours. The resulting hourly outputs are subsequently used to calculate hydrogen production and techno-economic performance metrics, including electrolyzer capacity factor and Levelized Cost of Hydrogen (LCOH). Techno-economic parameters such as CAPEX, OPEX, conversion efficiency, and project lifetime are integrated within the framework to evaluate overall system performance.

Through this approach, renewable resource variability, system sizing, and electrolyzer operational constraints are consistently captured within a unified techno-economic framework.

Alternative modeling approaches could treat solar PV generation directly on a DC basis and apply AC/DC conversion only to wind generation. However, in this study, both renewable sources are consistently treated on an AC basis to simplify integration within hybrid renewable configurations.

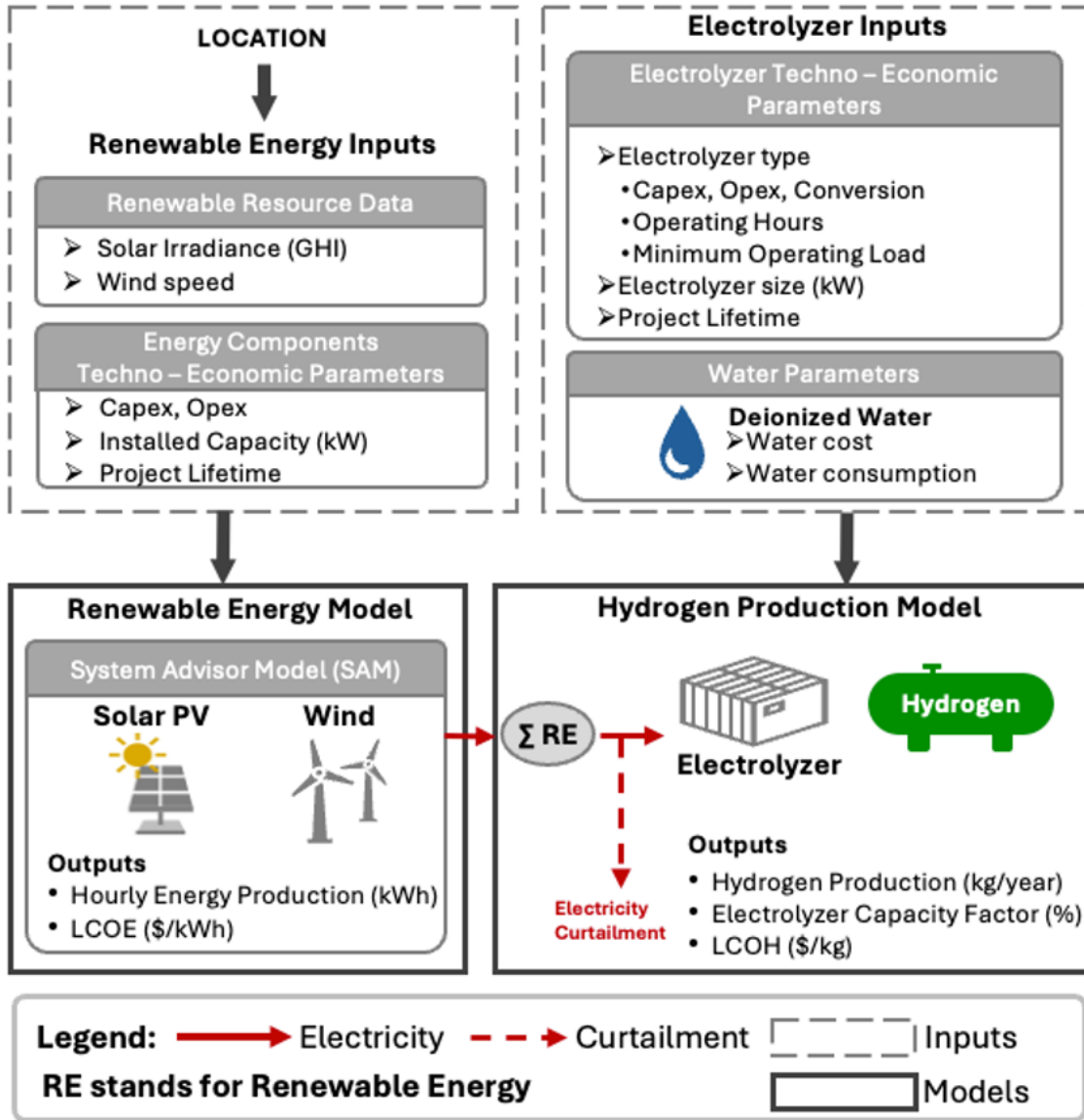


Figure 3.2: Data Treatment Workflow

3.2 Renewable Energy Modeling

Renewable electricity generation is simulated using the System Advisor Model (SAM), developed by the National Laboratory of the Rockies (NLR) [26]. Location inputs (latitude and longitude) are used to obtain hourly solar irradiance and wind speed data. Installed capacities (on an AC basis) and technology assumptions for solar and wind systems are defined, and SAM calculates hourly electricity production

for resource variability, system losses, and technology performance. It also provides the Levelized Cost of Electricity $LCOE$, expressed in (USD/kWh) for each component. To ensure consistency, the same PV and wind system specifications are applied across all locations.

For hybrid configurations, solar and wind generation are combined to determine the total renewable energy available to the hydrogen system, as shown in Eq. 3.1, where E_{PV} and E_{Wind} represent the annual solar and wind energy generation (kWh/year), respectively, and E_{mix} is their sum:

$$E_{mix} = E_{PV} + E_{Wind} \quad (3.1)$$

The effective LCOE of the hybrid system is calculated as an energy-weighted average, as shown in Eq. 3.2, where energy is expressed on an annual basis:

$$LCOE_{mix} = \frac{LCOE_{PV} \cdot E_{PV} + LCOE_{Wind} \cdot E_{Wind}}{E_{mix}} \quad (3.2)$$

Hybrid configurations enable the analysis of complementarities between solar and wind generation. Due to their distinct temporal patterns with solar generation peaking during daytime and wind generation often occurring at night, the combined profile can reduce intermittency and smooth short-term fluctuations as illustrated in Figure 3.3. This directly influences electrolyzer utilization, capacity factor, and curtailment. The resulting hybrid generation profile and LCOE are used as inputs to the electrolyzer operation model.

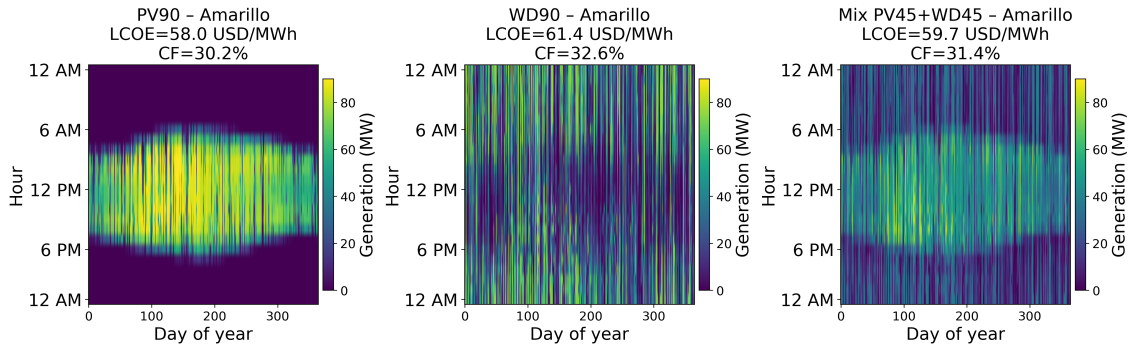


Figure 3.3: Energy complementarity for Amarillo-Texas, generated using SAM

3.3 Hydrogen Production Model

Rectifier and AC/DC Conversion

Electrolyzers operate with DC power, while renewable electricity generation obtained from SAM is treated on an AC power basis. Therefore, a rectifier stage is included between the renewable generation system and the electrolyzer to convert AC electricity into DC electricity.

The available power supplied to the electrolyzer is calculated as:

$$P_{\text{Available,DC}} = P_{\text{Available,AC}} \cdot \eta_{\text{Rectifier}} \quad (3.3)$$

where $P_{\text{Available,AC}}$ is the hourly renewable power generation obtained from SAM [kW AC], $\eta_{\text{Rectifier}}$ is the rectifier efficiency, and $P_{\text{Available,DC}}$ is the power available to the electrolyzer [kW DC]. Typical rectifier efficiencies range from 95% to 99% [27]; in this study, a rectifier efficiency of 97% is assumed.

Unless otherwise specified, all electrolyzer operational variables and power quantities presented in the following sections are expressed on a DC power basis.

Electrolyzer Operation

Electrolyzers operate under technical constraints that define their feasible operating range, including a minimum load threshold and a maximum rated capacity. Different electrolyzer technologies exhibit distinct minimum load requirements (PEM: 5%, AWE: 20%, SOEC: 30%) (Table 2.2).

When the available renewable power $P_{\text{Available}}$ [kW] falls below the minimum operating power $P_{\text{Electrolyzer,min}}$ [kW], the electrolyzer is assumed to shut down. Conversely, when the available power exceeds the electrolyzer installed capacity $P_{\text{Electrolyzer,size}}$ [kW], the excess power is curtailed. As a result, only a fraction of the available renewable energy is effectively utilized for hydrogen production.

The resulting electrolyzer power consumption $P_{\text{Electrolyzer}}$ [kW] is defined as:

$$P_{\text{Electrolyzer}} = \begin{cases} 0, & P_{\text{Available}} < P_{\text{Electrolyzer,min}} \\ P_{\text{Available}}, & P_{\text{Electrolyzer,min}} \leq P_{\text{Available}} \leq P_{\text{Electrolyzer,size}} \\ P_{\text{Electrolyzer,size}}, & P_{\text{Available}} > P_{\text{Electrolyzer,size}} \end{cases} \quad (3.4)$$

This operating behavior is illustrated in Figure 3.4, where three distinct regimes can be observed: shutdown below the minimum load, linear operation within the feasible range, and curtailment when available power exceeds the electrolyzer capacity.

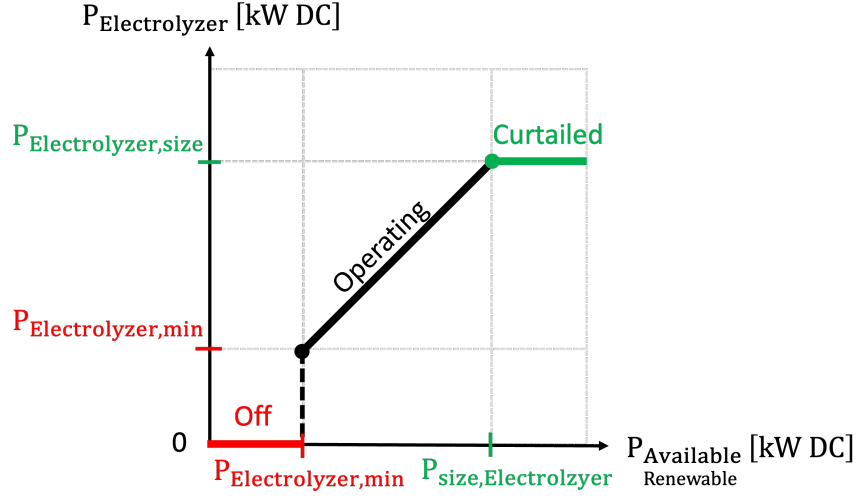


Figure 3.4: Electrolyzer operating range as a function of available renewable power

Higher minimum load thresholds reduce operational flexibility and increase unused energy, as illustrated in Figure 3.5.

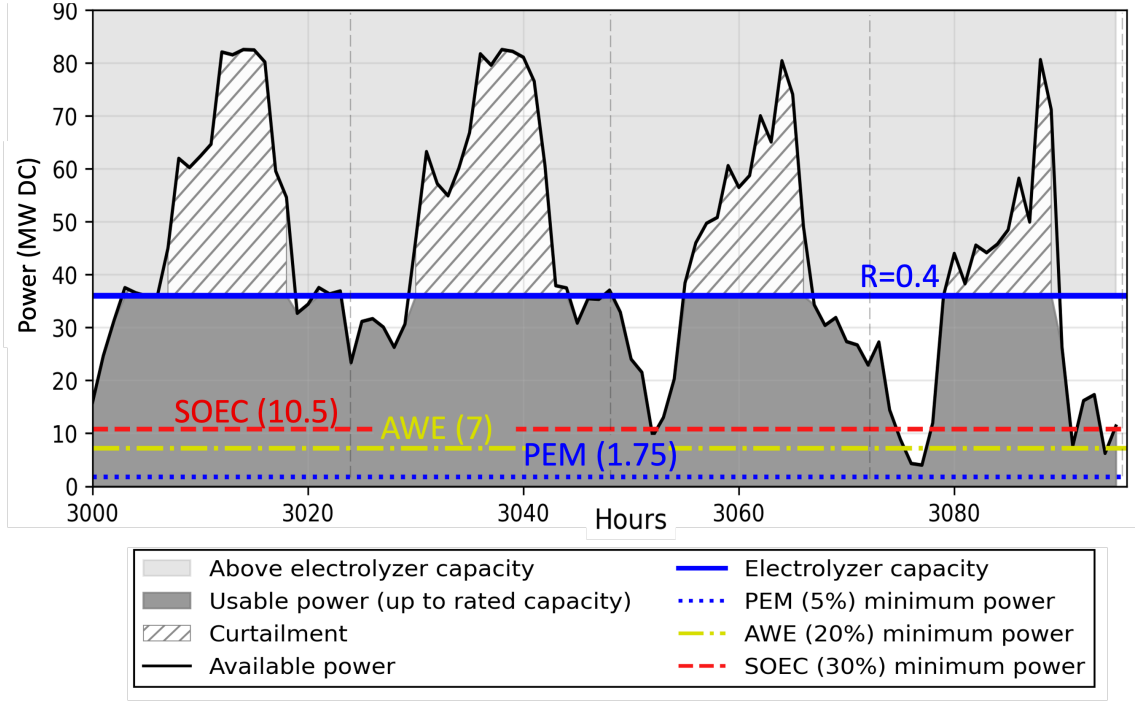


Figure 3.5: Electrolyzer operating range as a function of available renewable power for different technologies

Example: In the example shown, the renewable installed capacity is 90 MW AC and the electrolyzer installed capacity is 35 MW DC, corresponding to an electrolyzer-to-renewable capacity ratio of $R = 0.4$. The available renewable power shown in the figure is expressed on a DC basis after rectifier conversion. Therefore, power above 35 MW cannot be utilized by any technology. Considering the minimum load requirements of each electrolyzer technology, power below 1.75 MW is not usable for PEM, while the unusable power thresholds for AWE and SOEC are 7 MW and 10.5 MW, respectively.

The annual energy consumed by the electrolyzer $E_{\text{Electrolyzer}}$ [kWh/year] is given by:

$$E_{\text{Electrolyzer}} = \sum_{t=1}^{8760} P_{\text{Electrolyzer}} \Delta t \quad (3.5)$$

where Δt represents the hourly time step (1 hour).

The fraction of unused renewable energy is calculated as:

$$Unused\ Energy\ [\%] = \left(1 - \frac{E_{\text{Electrolyzer}}}{E_{\text{mix}}}\right) \times 100 \quad (3.6)$$

Electrolyzer-to-Renewable Capacity Ratio

The electrolyzer size is defined as a fraction of the installed renewable capacity through the electrolyzer-to-renewable capacity ratio R , as shown in Eq. 3.7:

$$R = \frac{P_{\text{Electrolyzer,size}}}{P_{\text{Renewable,size}} \cdot \eta_{\text{Rectifier}}} \quad (3.7)$$

where $P_{\text{Electrolyzer,size}}$ represents the electrolyzer installed capacity [kW DC], $P_{\text{Renewable,size}}$ represents the total installed renewable capacity [kW AC], and $\eta_{\text{Rectifier}}$ is the rectifier efficiency.

When $R < 1$, renewable capacity exceeds electrolyzer capacity, increasing electrolyzer utilization but leading to higher curtailment. When $R > 1$, the electrolyzer is oversized relative to renewable generation, reducing utilization. Values greater than one are not considered in this study due to the resulting low electrolyzer utilization.

Electrolyzer Capacity Factor

The electrolyzer capacity factor CF_{El} [%] is defined as:

$$CF_{\text{El}} = \frac{E_{\text{Electrolyzer}}}{P_{\text{Electrolyzer,size}} \cdot 8760} \times 100 \quad (3.8)$$

where $E_{\text{Electrolyzer}}$ is the annual energy processed by the electrolyzer [kWh/year], $P_{\text{Electrolyzer,size}}$ is the electrolyzer rated capacity [kW], and 8760 represents the total number of hours in a year.

Variations in R directly influence utilization: lower R increases the capacity factor, while higher R reduces it.

Hydrogen Production

Annual hydrogen production m_{H_2} [kg/year] is calculated as:

$$m_{\text{H}_2} = \frac{E_{\text{Electrolyzer}}}{e_{\text{El}}} \quad (3.9)$$

where $E_{\text{Electrolyzer}}$ is the annual energy processed by the electrolyzer [kWh/year], and e_{El} is the specific energy consumption (kWh/kg_{H₂}).

Water Consumption

Water consumption is assumed proportional to hydrogen production:

$$m_{\text{H}_2\text{O}} = m_{\text{H}_2} \cdot r_{\text{H}_2\text{O}/\text{H}_2} \quad (3.10)$$

where $m_{\text{H}_2\text{O}}$ is the annual water consumption, m_{H_2} is the annual hydrogen production [kg/year], and $r_{\text{H}_2\text{O}/\text{H}_2}$ is the specific water consumption, assumed to be 10 kg/kg_{H₂}.

The unit cost of deionized water is assumed to be 0.01 USD/kg [17].

3.4 Economic Model

The Levelized Cost of Hydrogen (LCOH) represents the discounted average cost per unit of hydrogen produced over the project lifetime [USD/kg]. Following [17], it is defined as:

$$\text{LCOH} = \frac{NPC_{\text{energy}} + NPC_{\text{Electrolyzer}} + \sum_{n=1}^{PL} \frac{C_{\text{H}_2\text{O},n}}{(1+d)^n}}{\sum_{n=1}^{PL} \frac{m_{\text{H}_2,n}}{(1+d)^n}} \quad (3.11)$$

where:

- NPC_{energy} is the net present cost of the renewable energy system [USD]
- $NPC_{\text{Electrolyzer}}$ is the net present cost of the electrolyzer system [USD]
- $C_{\text{H}_2\text{O},n}$ is the annual cost of deionized water in year n [USD/year]
- $m_{\text{H}_2,n}$ is the hydrogen production in year n [kg/year]
- d is the discount rate.
- PL is the project lifetime [years]

All costs and hydrogen production are discounted to present value to account for the time value of money.

Discount Factor

Future cash flows are discounted to present value using a constant annual discount rate d . The general formulation for the net present value (NPV) of a future cash flow F_n occurring in year n is [28]:

$$NPV = \sum_{n=1}^{PL} \frac{F_n}{(1+d)^n} \quad (3.12)$$

For uniform annual cash flows, the present value can be expressed using the annuity factor [28]:

$$NPV = F \cdot \frac{1 - (1+d)^{-PL}}{d} \quad (3.13)$$

Future cash flows are discounted using a constant annual discount rate d . For uniform annual values, the present value is calculated using the annuity factor [28]:

$$DF = \frac{1 - (1+d)^{-PL}}{d} \quad (3.14)$$

Using this factor, Eq. 3.11 can be expressed in compact form as:

$$LCOH = \frac{NPC_{\text{energy}} + NPC_{\text{Electrolyzer}} + C_{\text{H}_2\text{O},\text{annual}} \cdot DF}{m_{\text{H}_2,\text{annual}} \cdot DF} \quad (3.15)$$

A discount rate of 8% is assumed [17].

Water Cost

The annual water cost $C_{\text{H}_2\text{O}}$ [USD/year] is calculated as:

$$C_{\text{H}_2\text{O}} = m_{\text{H}_2\text{O}} \cdot c_{\text{water}} \quad (3.16)$$

where $m_{\text{H}_2\text{O}}$ is the annual water consumption [kg/year], and c_{water} is the unit cost of water [USD/kg], assumed to be 0.01 USD/kg [17].

Net Present Cost of Energy

Renewable system costs are represented through the Levelized Cost of Electricity (LCOE), expressed in USD/kWh and obtained from SAM simulations. Since

the system is modeled as off-grid, with no electricity export or storage, all generated electricity—including curtailed energy—is economically allocated to hydrogen production.

The net present cost of renewable electricity over the project lifetime is therefore calculated as:

$$NPC_{\text{energy}} = LCOE_{\text{mix}} \cdot E_{\text{mix,annual}} \cdot DF \quad (3.17)$$

Net Present Cost of the Electrolyzer

The net present cost of the electrolyzer system is defined as:

$$NPC_{\text{Electrolyzer}} = CAPEX_{\text{Electrolyzer}} + NPC_{\text{OPEX}} + NPC_{\text{replacement}} - S_{\text{stack}} \quad (3.18)$$

The electrolyzer capital cost is calculated as:

$$CAPEX_{\text{Electrolyzer}} = c_{\text{capex}} \cdot P_{\text{Electrolyzer}} \quad (3.19)$$

where c_{capex} and c_{opex} are expressed in USD/kW and USD/kW-year, respectively.

The annual operating cost is:

$$OPEX_{\text{annual}} = c_{\text{opex}} \cdot P_{\text{Electrolyzer}} \quad (3.20)$$

and its net present value is:

$$NPC_{\text{OPEX}} = OPEX_{\text{annual}} \cdot DF \quad (3.21)$$

Stack Replacement and Salvage Value

Electrolyzer stack lifetime H_{stack} [hours] is defined in operating hours, as shown in Table 2.2, while the project lifetime (PL) is defined in years (20 years in this study) [28]. Due to intermittent operation under variable renewable supply, the effective calendar lifetime of the stack depends on the annual operating hours (h_{active}) [29], which vary with system design, resource availability, and the sizing ratio R .

The equivalent time between stack replacements is:

$$Y_{\text{replacement}} = \frac{H_{\text{stack}}}{h_{\text{active}}} \quad (3.22)$$

The replacement cost is assumed as a fraction α of the electrolyzer capital cost:

$$C_{\text{replacement}} = \alpha \text{CAPEX}_{\text{Electrolyzer}} \quad (3.23)$$

with $\alpha = 0.11$ [17].

The number of replacements within the PL is:

$$N_{\text{replacement}} = \left\lfloor \frac{PL}{Y_{\text{replacement}}} \right\rfloor \quad (3.24)$$

Each replacement is discounted to present value:

$$NPC_{\text{replacement}} = \sum_{k=1}^{N_{\text{replacement}}} \frac{C_{\text{replacement}}}{(1+d)^k Y_{\text{replacement}}} \quad (3.25)$$

At the end of the project lifetime, the remaining fraction of stack lifetime is:

$$f_{\text{remaining}} = \max \left(0, 1 - \frac{PL - N_{\text{replacement}} Y_{\text{replacement}}}{Y_{\text{replacement}}} \right) \quad (3.26)$$

The corresponding salvage value is:

$$S_{\text{stack}} = \frac{f_{\text{remaining}} C_{\text{replacement}}}{(1+d)^{PL}} \quad (3.27)$$

This salvage value represents the residual economic value of the stack at the end of the analysis period and is treated as a positive cash flow discounted to present value, consistent with standard economic evaluation practices [28, 29].

3.5 System Boundaries and Assumptions

- The system is modeled as off-grid: electricity is not sold to the grid, and no grid connection or battery storage is considered.
- The project lifetime is assumed to be 20 years, consistent with both the SAM simulations and the LCOH calculations. A constant discount rate of 8% is applied throughout the analysis.

- The effective operating time and salvage value of the electrolyzer stack are adjusted based on actual utilization.

Chapter 4

BASELINE STUDY

The objective of the baseline analysis is to evaluate how renewable resource availability, energy mix, electrolyzer technology, and the electrolyzer-to-renewable capacity ratio (R) influence hydrogen production and the Levelized Cost of Hydrogen (LCOH). To ensure comparability, a common set of techno-economic assumptions is applied across all locations. This baseline analysis identifies general cost trends and optimal system configurations prior to the sensitivity analyses presented in Chapter 5.

4.1 Energy and Electrolyzer Techno-Economic Parameters

The techno-economic performance of the modeled systems is defined by a set of key parameters for renewable generation and electrolyzer technologies. These include capital and operational costs, conversion efficiency, operational lifetime, and minimum load constraints, which directly influence system utilization and the Levelized Cost of Hydrogen (LCOH).

Renewable energy simulations were performed in SAM using consistent technology assumptions across all locations.

Solar PV system assumptions:

- System capacity: 90 MW AC
- DC-to-AC ratio: 1.3
- Module type: Standard
- Inverter efficiency: 96%
- Array configuration: Single-axis tracking
- Total system losses: 14%

PV system losses include soiling, shading, mismatch, wiring, connections, light-induced degradation, nameplate losses, and availability losses. These values correspond to the default assumptions implemented in SAM.

Wind system assumptions:

- Turbine model: GE 2.5xl
- Hub height: 80 m
- Shear coefficient: 0.14
- Wind farm installed capacity: 90 MW AC
- Wake model: Simple Wake Model
- Turbulence coefficient: 0.1

Wind system losses considered in SAM include wake losses (1.1%), availability losses (5.5%), electrical losses (2.0%), turbine performance losses (3.95%), environmental losses (2.4%), and curtailment and operational losses (2.8%). These values correspond to the default assumptions implemented in SAM.

The techno-economic parameters considered for renewable generation and electrolyzer technologies are summarized in Tables 4.1 and 4.2, respectively.

Table 4.1: Economic parameters for renewable generation [30]

Parameter	Solar	Wind
CAPEX [USD/kW]	1,432	1,537
OPEX [USD/kW-y]	20.40	30.86

Table 4.2: Techno-economic parameters for electrolyzer technologies [17]

Parameter	AWE	PEM	SOEC
CAPEX [USD/kW]	1,451	1,627	3,562
OPEX [USD/kW-y]	73	82	178
Stack lifetime [h]	70,080	52,560	43,800
Specific energy consumption [kWh/kg H ₂]	50.1	46.7	41.2
Minimum load [%]	20	5	30

Additional assumptions include a rectifier efficiency $\eta_{\text{Rectifier}}$ of 97% [27], a specific water consumption ($r_{\text{H}_2\text{O}/\text{H}_2}$) of 10 kg/kg $_{\text{H}_2}$ [17], a deionized water cost of 0.01 USD/kg [17], a project lifetime of 20 years, and a discount rate of 8% [17]. These assumptions are used to evaluate system performance and calculate the Levelized Cost of Hydrogen (LCOH) through a discounted cash flow approach (Chapter 3). Overall, these assumptions play a critical role in defining system performance and strongly influence electrolyzer utilization, capacity factor, hydrogen production, and the resulting Levelized Cost of Hydrogen (LCOH).

4.2 Location Selection

The objective of the location selection process is to identify sites that represent different degrees of solar–wind complementarity, rather than simply selecting locations with the highest renewable capacity factor. This enables the evaluation of how hourly resource complementarity affects hydrogen production, electrolyzer utilization, and LCOH.

The selection methodology targeted locations representing the following categories:

- High solar – Low wind
- High solar – High wind
- Low solar – High wind
- Low solar – Low wind

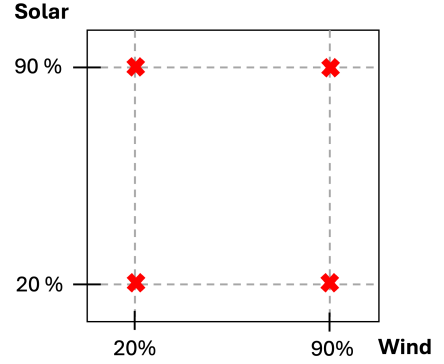


Figure 4.1: Location selection methodology based on renewable resource complementarity.

The selection of candidate locations was supported by renewable resource maps from the National Laboratory of the Rockies (NLR), including the National Solar Radiation Database (NSRDB) [31], as shown in Figure 4.2. A total of 13 locations were selected to represent contrasting renewable resource conditions across the United States, as listed in Table 4.3 and shown in Figure 4.3. Under consistent

installed capacities and technology assumptions, these locations produce distinct renewable generation profiles used to model hydrogen production and evaluate its cost.

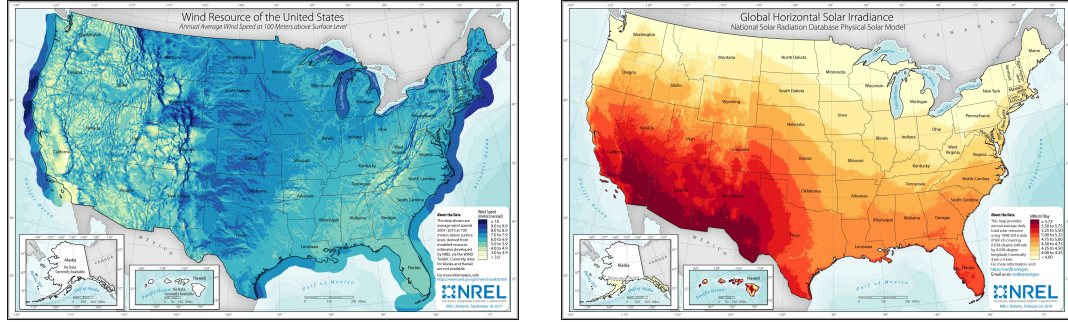


Figure 4.2: Wind and solar resource distribution across the United States.

Table 4.3: Geographic coordinates of analyzed locations

Location	Latitude (°)	Longitude (°)
Albuquerque – New Mexico	35.09	-106.66
Amarillo – Texas	35.21	-101.82
Bismarck – North Dakota	46.81	-100.78
Casper – Wyoming	42.85	-106.34
Columbia – South Carolina	34.01	-81.06
Durango – Colorado	37.29	-107.86
Huntsville – Alabama	34.73	-86.58
Orlando – Florida	28.53	-81.38
Phoenix – Arizona	33.45	-112.06
Pullman – Washington	46.73	-117.18
Rio Vista – California	38.17	-121.70
Salem – Oregon	44.93	-123.06
Sandpoint – Idaho	48.29	-116.54

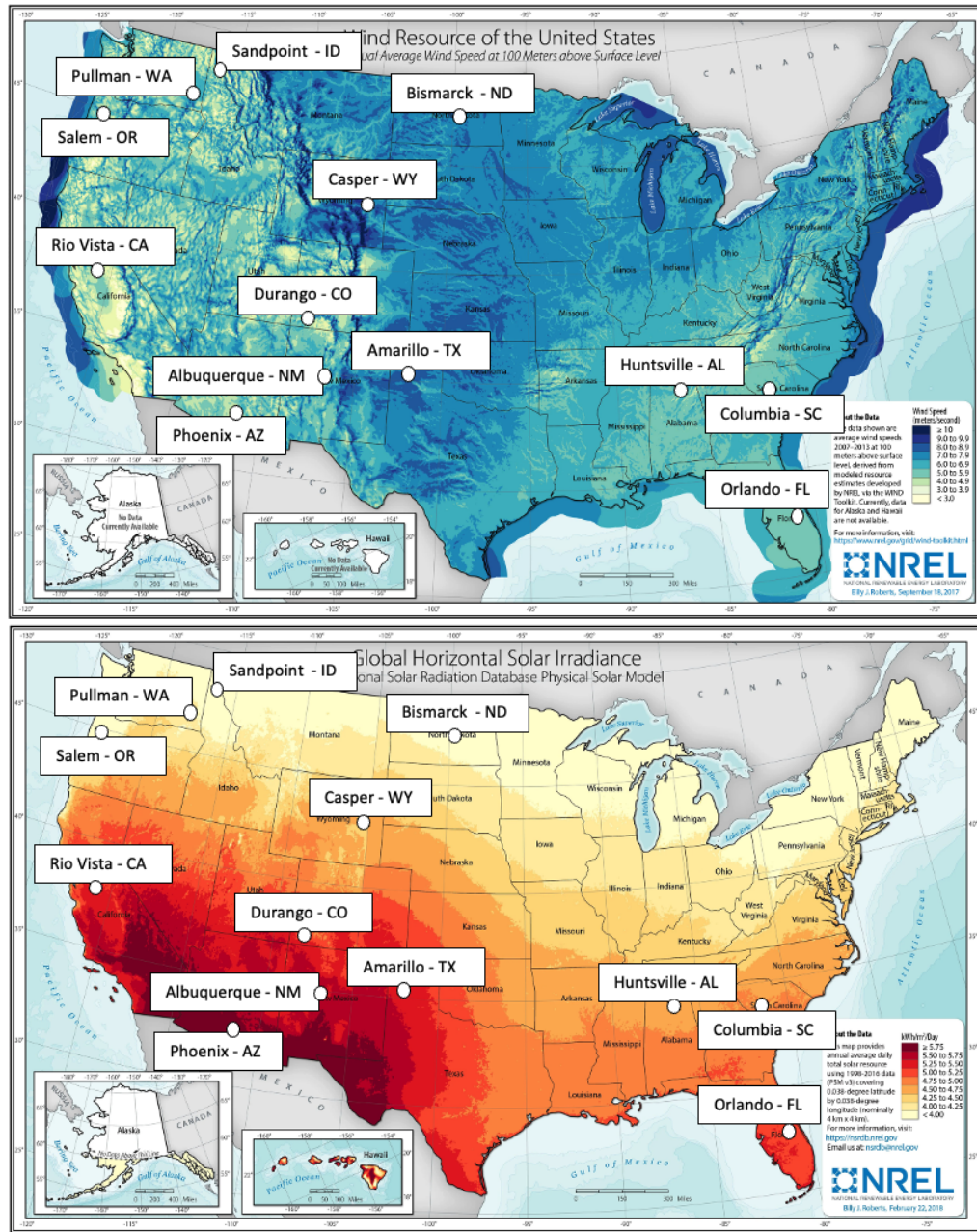


Figure 4.3: Wind and solar resource potential for the selected candidate locations.

SAM simulations [26] were conducted for all candidate locations under consistent installed capacity and technology assumptions to estimate renewable energy production. The results were normalized to compare relative solar and wind resource

performance, leading to the classification shown in Figure 4.4.

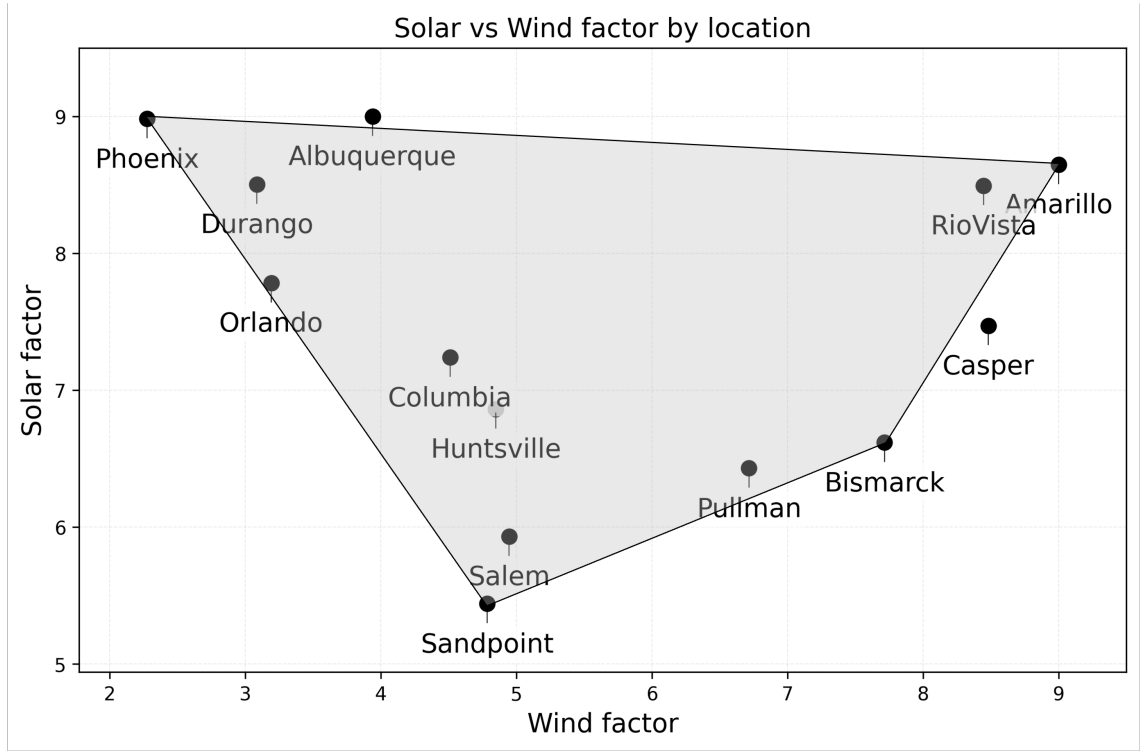


Figure 4.4: Relative solar and wind resource quality for the candidate locations based on normalized SAM energy production.

Based on this classification, four representative locations were selected for detailed analysis:

- Phoenix: solar-dominant conditions
- Sandpoint: low renewable resource availability
- Bismarck: wind-dominant conditions with moderate solar contribution
- Amarillo: strong solar–wind complementarity

Although no location with exclusively wind-dominant behavior and negligible solar contribution was identified, Bismarck represents the closest case within the candidate set.

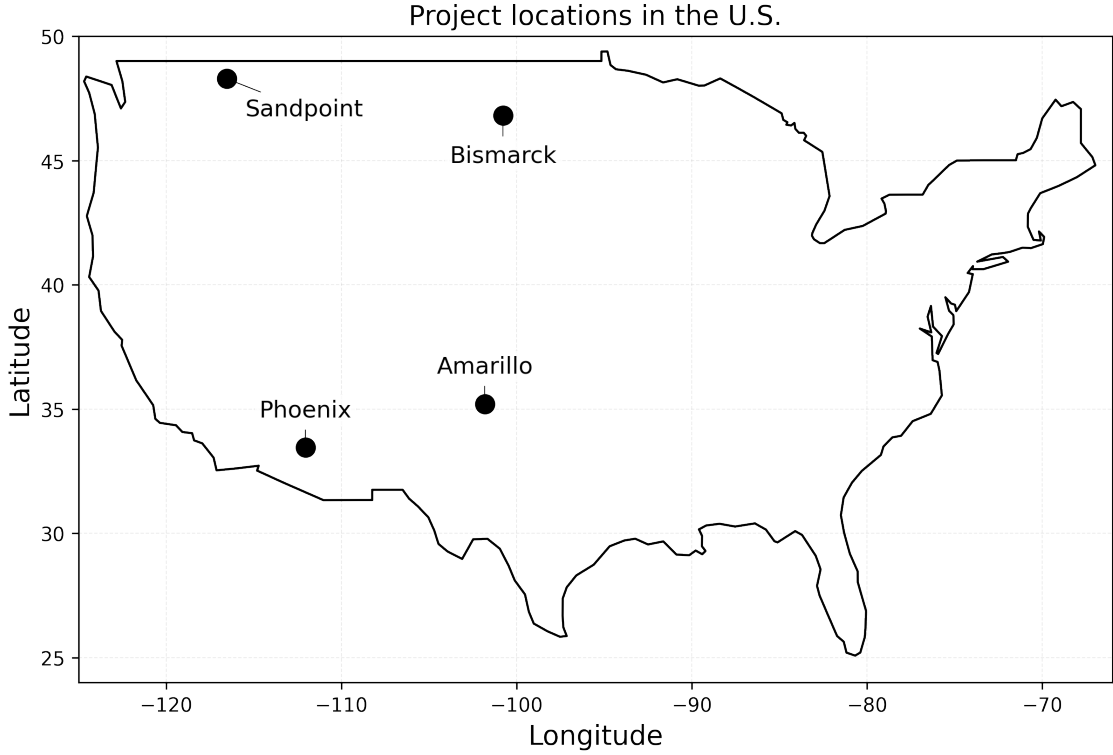


Figure 4.5: Geographic distribution of the selected locations.

4.3 Renewable Resource Characterization

The renewable generation profiles obtained from SAM show significant differences across locations due to variations in resource availability and seasonal patterns. Solar generation typically peaks during daytime hours, while wind generation often contributes more during nighttime periods. Hybrid solar–wind configurations improve the temporal distribution of generation by combining complementary resource patterns, increasing electrolyzer operating hours and overall utilization. This effect is particularly evident in locations with balanced resources, such as Amarillo and Bismarck.

Energy simulations were performed assuming a total installed renewable capacity of 90 MW AC. Five representative configurations were evaluated to illustrate renewable complementarity:

- 90 MW PV
- 60 MW PV + 30 MW wind

- 45 MW PV + 45 MW wind
- 30 MW PV + 60 MW wind
- 90 MW wind

Figure 4.6 shows the hourly generation patterns for the different locations and selected energy configurations (PV-only, hybrid PV45-WD45, and wind-only).

Although hybrid PV–wind systems may exhibit intermediate renewable capacity factors compared to single-resource systems, their improved temporal distribution increases electrolyzer utilization. This reduction in intermittency can ultimately lower LCOH, even when the renewable capacity factor is not maximized.

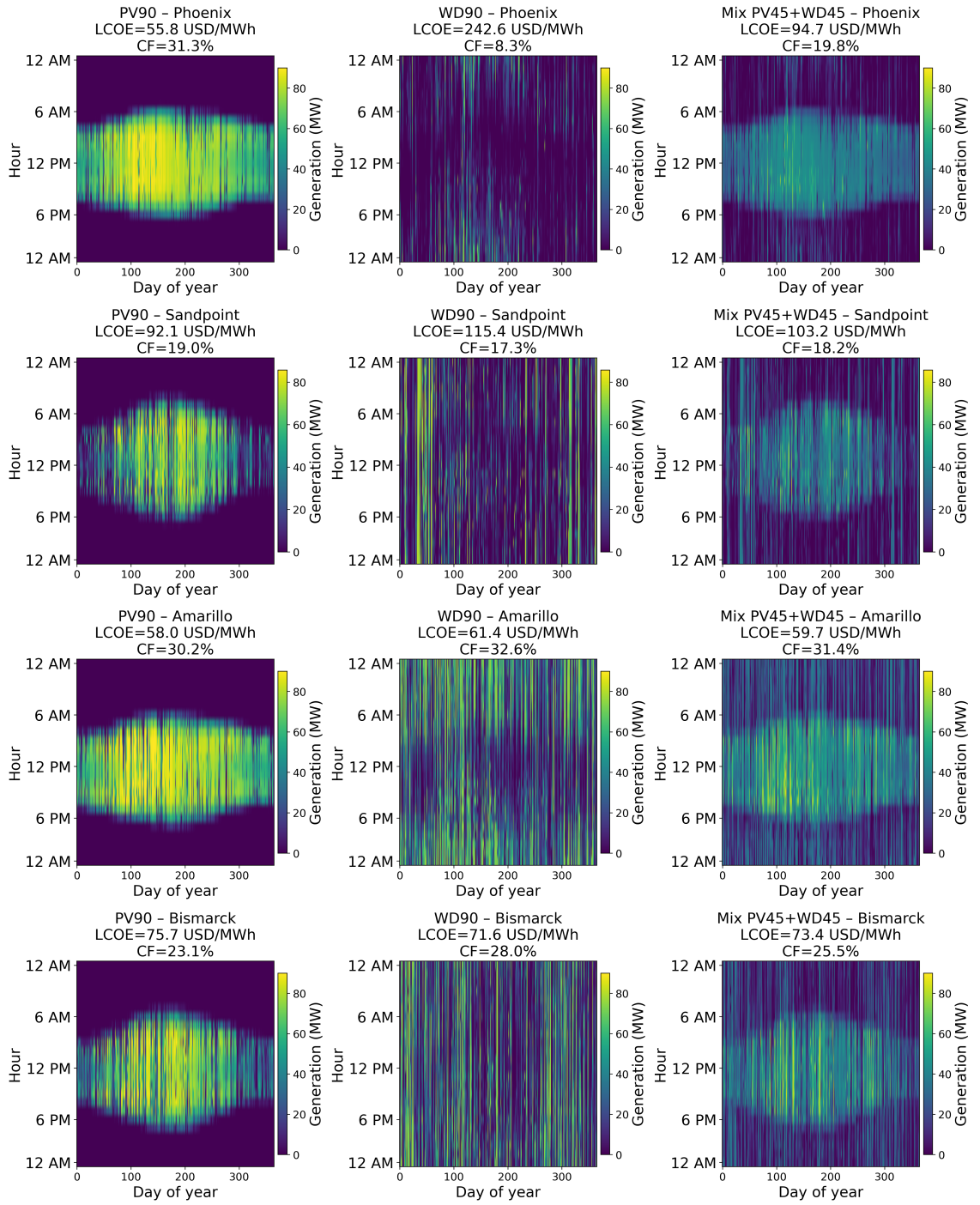


Figure 4.6: Hourly renewable generation heatmaps for the selected locations and representative PV-wind configurations.

4.4 Baseline Scenario

The baseline simulations evaluate hydrogen production and the Levelized Cost of Hydrogen (LCOH) across different locations, renewable configurations, and electrolyzer technologies under consistent techno-economic assumptions.

Simulations were performed considering:

- Four locations: Phoenix, Sandpoint, Bismarck, and Amarillo
- Three electrolyzer technologies: PEM, AWE, and SOEC
- Five renewable configurations: PV90, PV60-WD30, PV45-WD45, PV30-WD60, and WD90
- Electrolyzer-to-renewable capacity ratio (R) ranging from 0.2 to 1

In all cases, the total installed renewable capacity was maintained constant at 90 MW AC to ensure consistent comparison between renewable configurations.

The model described in Chapter 3 was applied to estimate renewable energy generation, electrolyzer performance, hydrogen production, and LCOH for each scenario. For each case, the optimal electrolyzer-to-renewable capacity ratio (R) and the corresponding electrolyzer capacity factor were identified at the minimum LCOH. The baseline simulations evaluate hydrogen production and the Levelized Cost of Hydrogen (LCOH) across different locations, renewable configurations, and electrolyzer technologies under consistent techno-economic assumptions.

4.4.1 Minimum LCOH Across Locations

Figure 4.7 and Figure 4.8 shows the minimum LCOH obtained for each location across renewable configurations and electrolyzer technologies, together with the corresponding electrolyzer-to-renewable capacity ratio (R) and the corresponding electrolyzer capacity factor ($CF\%$).

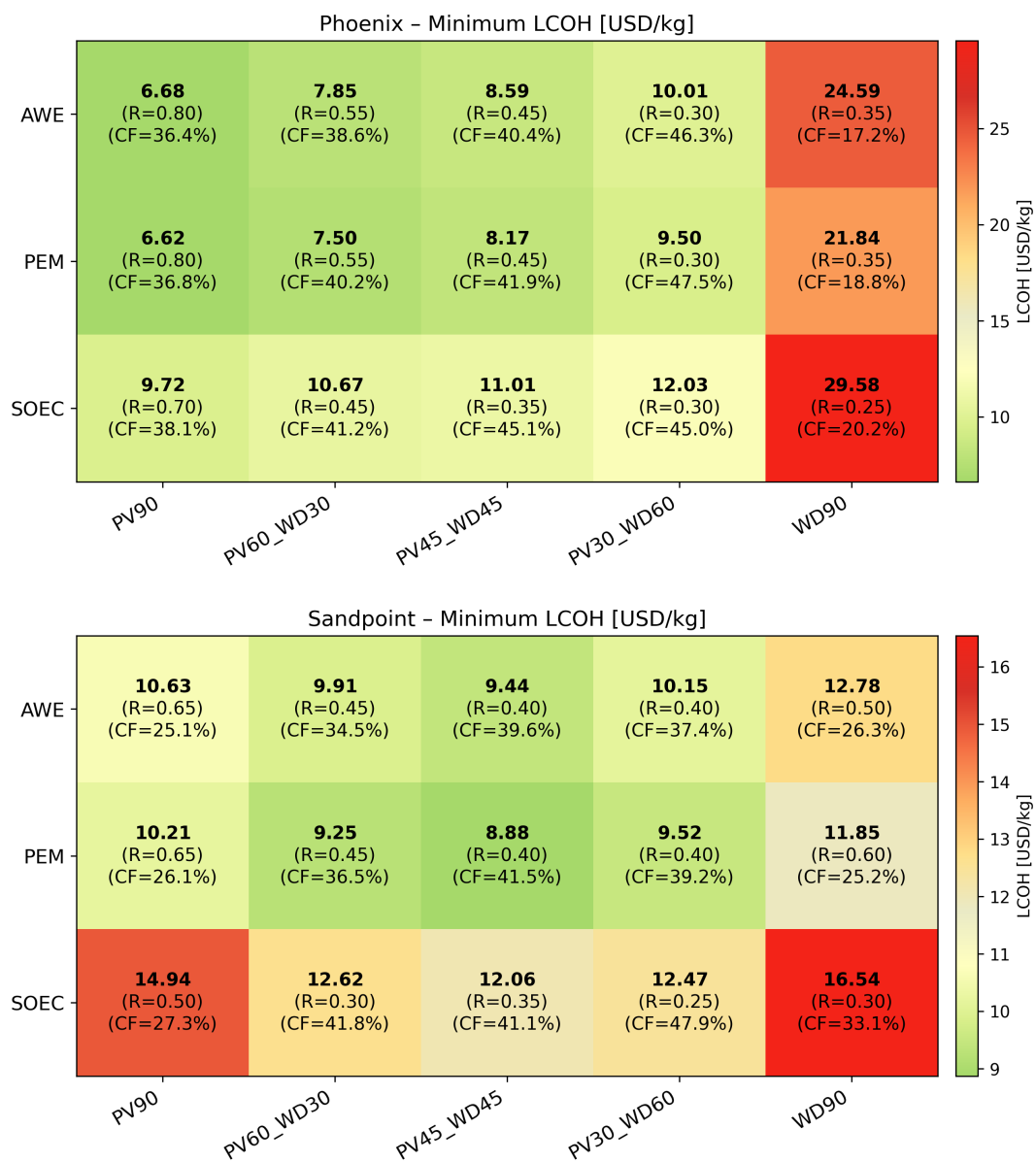


Figure 4.7: Minimum LCOH obtained for Phoenix and Sandpoint.

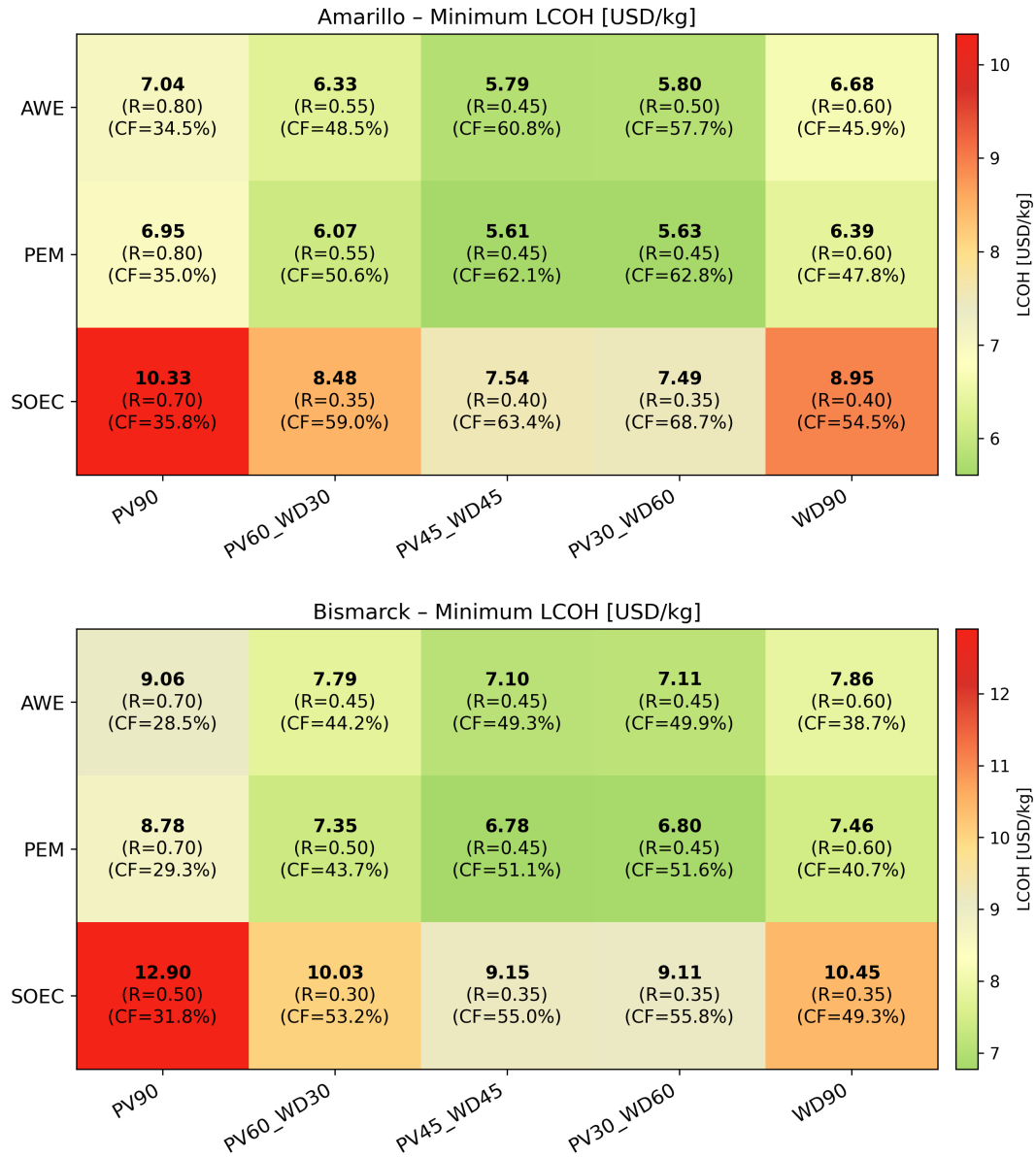


Figure 4.8: Minimum LCOH obtained for Bismarck and Amarillo.

Clear relationships between renewable resource characteristics and optimal system configuration can be observed. Phoenix is dominated by solar resources, leading to the lowest LCOH under PV-only configurations, while wind-based systems are less competitive. Sandpoint exhibits relatively low availability of both solar and wind resources, resulting in high LCOH values across all configurations, with only limited benefits from hybridization.

In contrast, Amarillo shows strong solar–wind complementarity, where hybrid configurations achieve the lowest LCOH due to improved temporal distribution of generation and higher electrolyzer utilization. Bismarck exhibits wind-dominant conditions with moderate solar contribution, where wind and hybrid configurations show similar LCOH values, indicating that adding solar does not significantly increase cost while potentially improving system robustness.

Regarding electrolyzer technologies, PEM consistently achieves the lowest LCOH across all locations, with AWE yielding similar values in several cases. In contrast, SOEC exhibits the highest LCOH due to its higher capital cost and shorter lifetime, which increase replacement costs.

Among all locations, Amarillo yields the lowest LCOH (5.61 USD/kg), primarily due to its strong resource complementarity and resulting high electrolyzer utilization.

Table 4.4: Minimum LCOH configuration for each location

Location	Energy configuration	Electrolyzer	LCOH (USD/kg H ₂)	R ratio	CF (%)	H ₂ (Mkg/y)	Unused energy (%)
Phoenix	PV90	PEM	6.62	0.80	36.8	4.82	6.0
Sandpoint	PV45_WD45	PEM	8.88	0.40	41.5	2.72	8.6
Bismarck	PV45_WD45	PEM	6.78	0.45	51.1	3.77	9.9
Amarillo	PV45_WD45	PEM	5.61	0.45	62.1	4.58	11.0

Table 4.4 summarizes the minimum LCOH for each location, including the corresponding configuration, electrolyzer technology, optimal R , capacity factor, and hydrogen production. Figure 4.9 shows the optimal configuration for each location within the renewable resource classification space, while Figure 4.10 presents their geographic distribution.

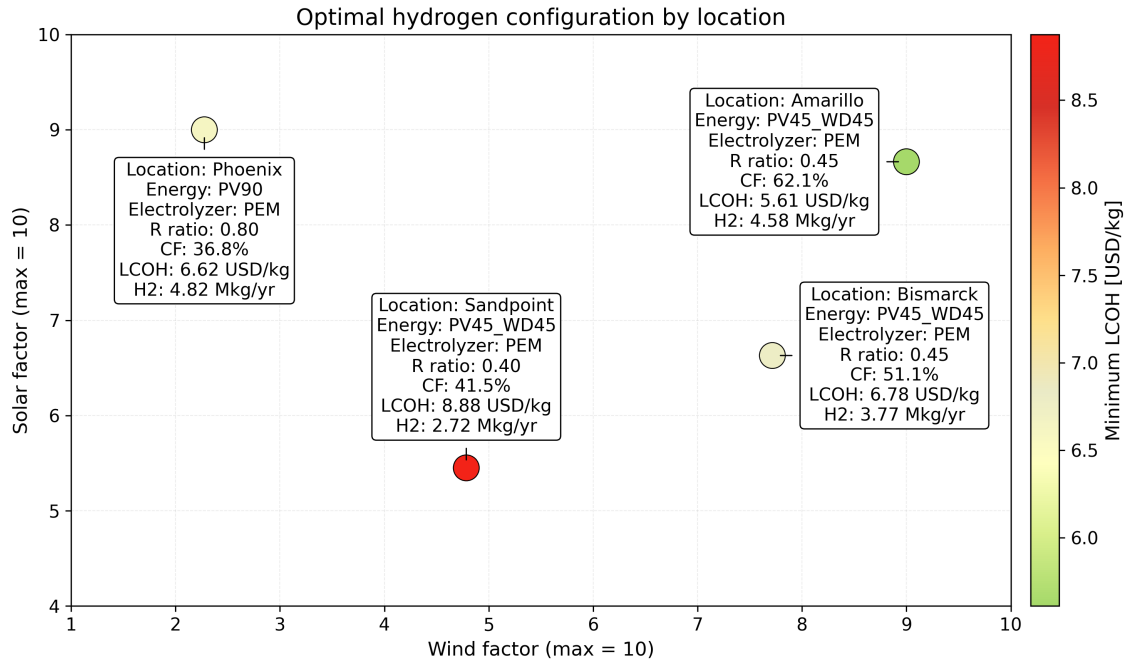


Figure 4.9: Optimal system configuration for each selected location in the renewable resource classification space.

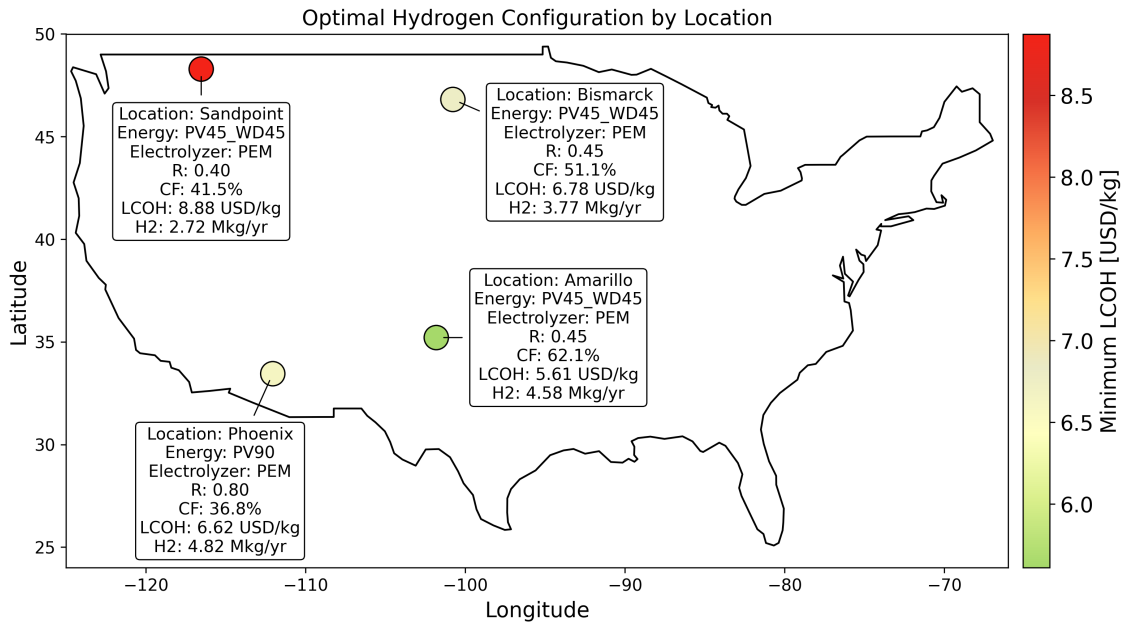


Figure 4.10: Optimal LCOH configuration by location.

Since PEM is the lowest-cost electrolyzer technology in the baseline analysis, Figure 4.11 compares the minimum LCOH across locations for different renewable configurations under fixed PEM operation. The results show a strong dependence on local resource conditions. In Phoenix, characterized by high solar availability, the lowest LCOH is obtained with the PV90 configuration. In Bismarck, which represents the closest case to wind-dominant conditions with moderate solar contribution, hybrid configurations (PV45-WD45) and wind-only systems (WD90) yield similar LCOH values. In Amarillo, the PV45-WD45 configuration achieves the lowest LCOH, although nearby configurations such as PV30-WD60 show comparable performance, indicating flexibility in capturing resource complementarity. In contrast, Sandpoint exhibits low availability of both solar and wind resources, resulting in higher LCOH across all configurations; however, hybrid systems still provide the lowest cost among the available options.

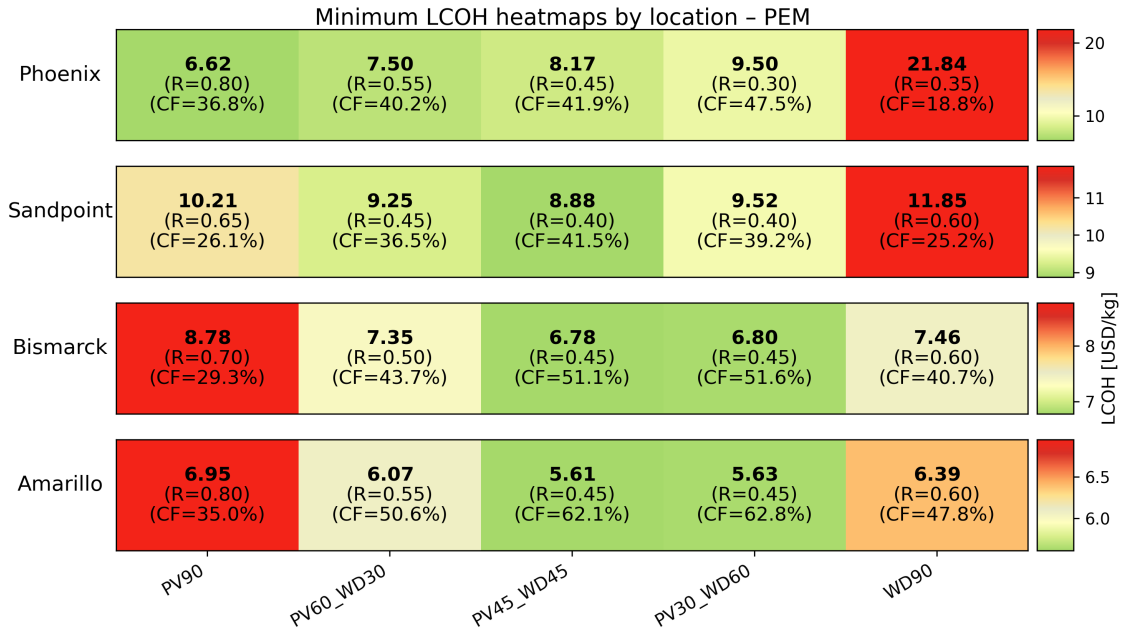


Figure 4.11: Minimum LCOH for the selected locations under PEM operation

The best baseline case corresponds to Amarillo-Texas with a PV45-WD45 configuration and PEM electrolyzer, achieving an optimal R of 0.45, a capacity factor of 62.1%, hydrogen production of 4.58 Mkg/year, and an LCOH of 5.61 USD/kg.

4.4.2 LCOH Trends as Function of R

Figure 4.12 shows the variation of LCOH, hydrogen production, electrolyzer capacity factor, and unused energy as a function of the sizing ratio R for Amarillo and Phoenix, respectively.

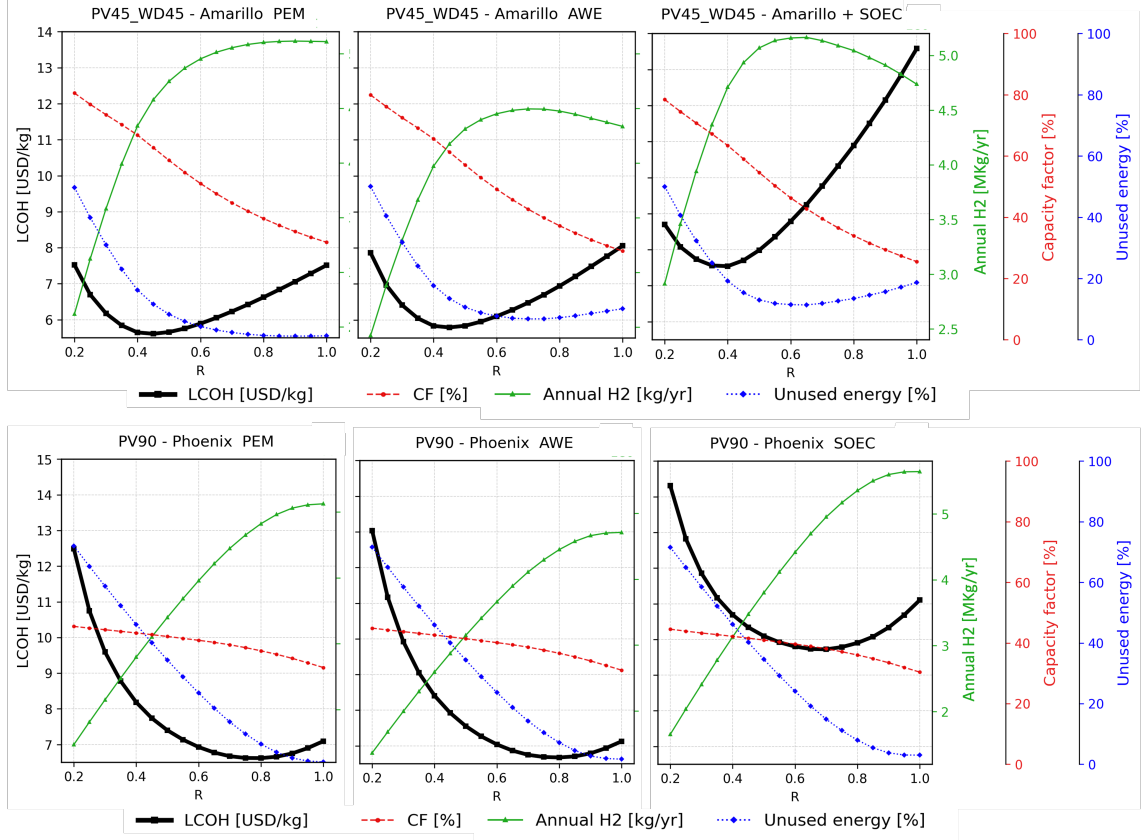


Figure 4.12: LCOH, hydrogen production, electrolyzer capacity factor, and unused energy as a function of the sizing ratio R for different locations and electrolyzer technologies.

The LCOH curves exhibit the characteristic convex behavior associated with electrolyzer sizing. At low values of R , LCOH is high due to significant renewable curtailment despite high electrolyzer utilization. As R increases, curtailment decreases and hydrogen production increases, leading to lower LCOH. Beyond the optimal point, further increases in R result in under-utilization of the electrolyzer,

causing LCOH to rise again. This behavior reflects the fundamental trade-off between renewable energy utilization and electrolyzer investment. At low R , system cost is renewable-dominated, while at high R , it becomes electrolyzer-dominated.

Unused energy follows a similar non-monotonic trend. Initially, it decreases as curtailment is reduced with increasing R . However, beyond a certain point, unused energy increases due to the minimum operating threshold, which prevents electrolyzer operation during periods of low renewable output. This effect is more pronounced for SOEC systems due to their higher minimum load requirement (30%), which limits operation during low-power periods and reduces effective energy utilization. It is also more evident in hybrid configurations than in PV-only systems, as solar generation tends to be more concentrated during daytime hours, allowing the electrolyzer to operate more consistently once the production threshold is reached.

Regarding electrolyzer technologies, PEM and AWE exhibit similar behavior due to comparable efficiencies and capital costs. In contrast, SOEC shows higher LCOH values due to its higher capital cost and more restrictive operating constraints, particularly its higher minimum load requirement (30%). Figures 4.13 compare the performance of the three electrolyzer technologies for the optimal renewable configurations in Amarillo and Phoenix, respectively.

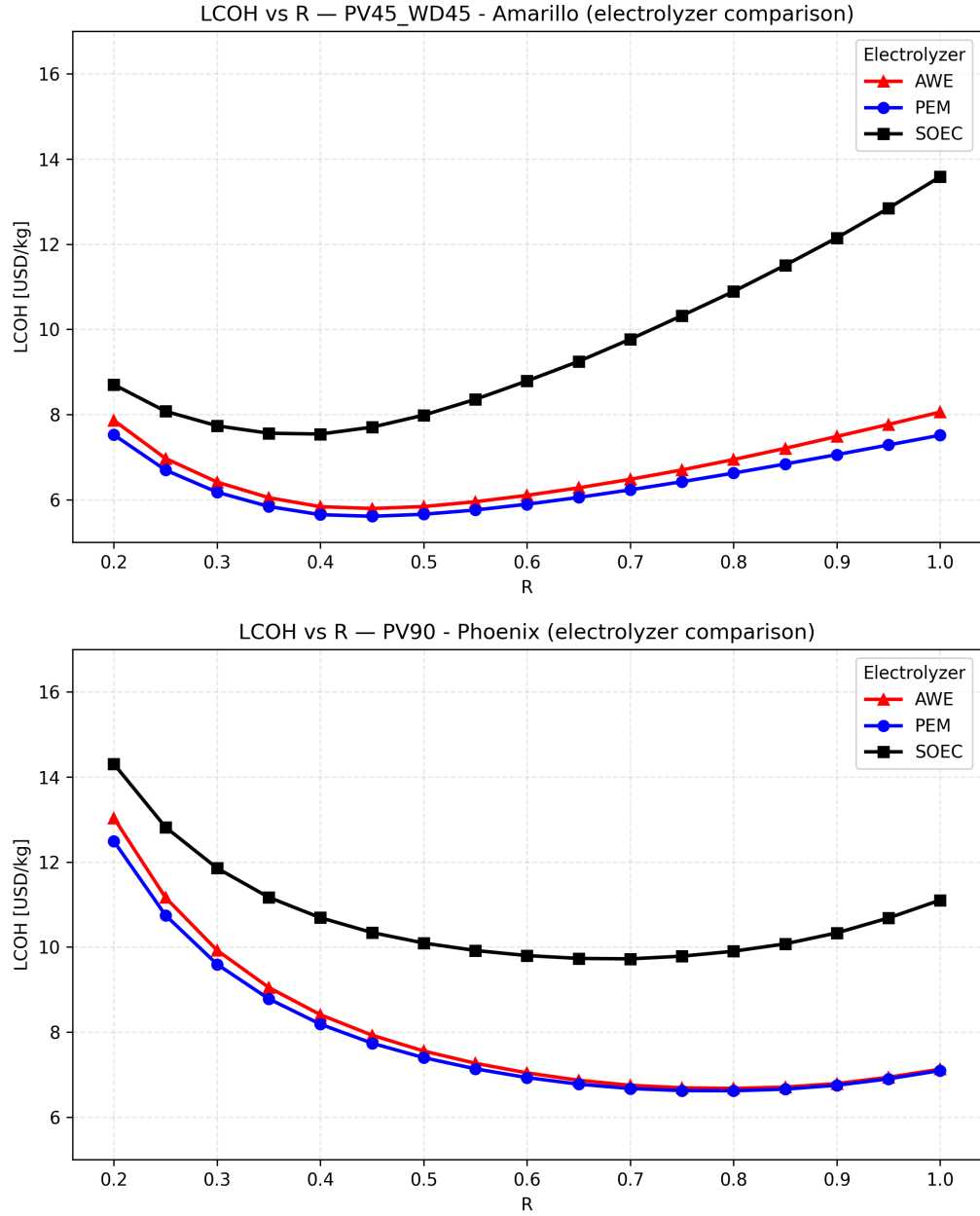


Figure 4.13: LCOH comparison across electrolyzer technologies for the optimal for Amarillo and Phoenix.

Figure 4.14 compares renewable configurations for Amarillo and Phoenix under PEM operation. All configurations exhibit convex LCOH behavior as a function of R , confirming that the sizing trade-off is intrinsic to the system. However, the

optimal configuration depends strongly on local resource conditions.

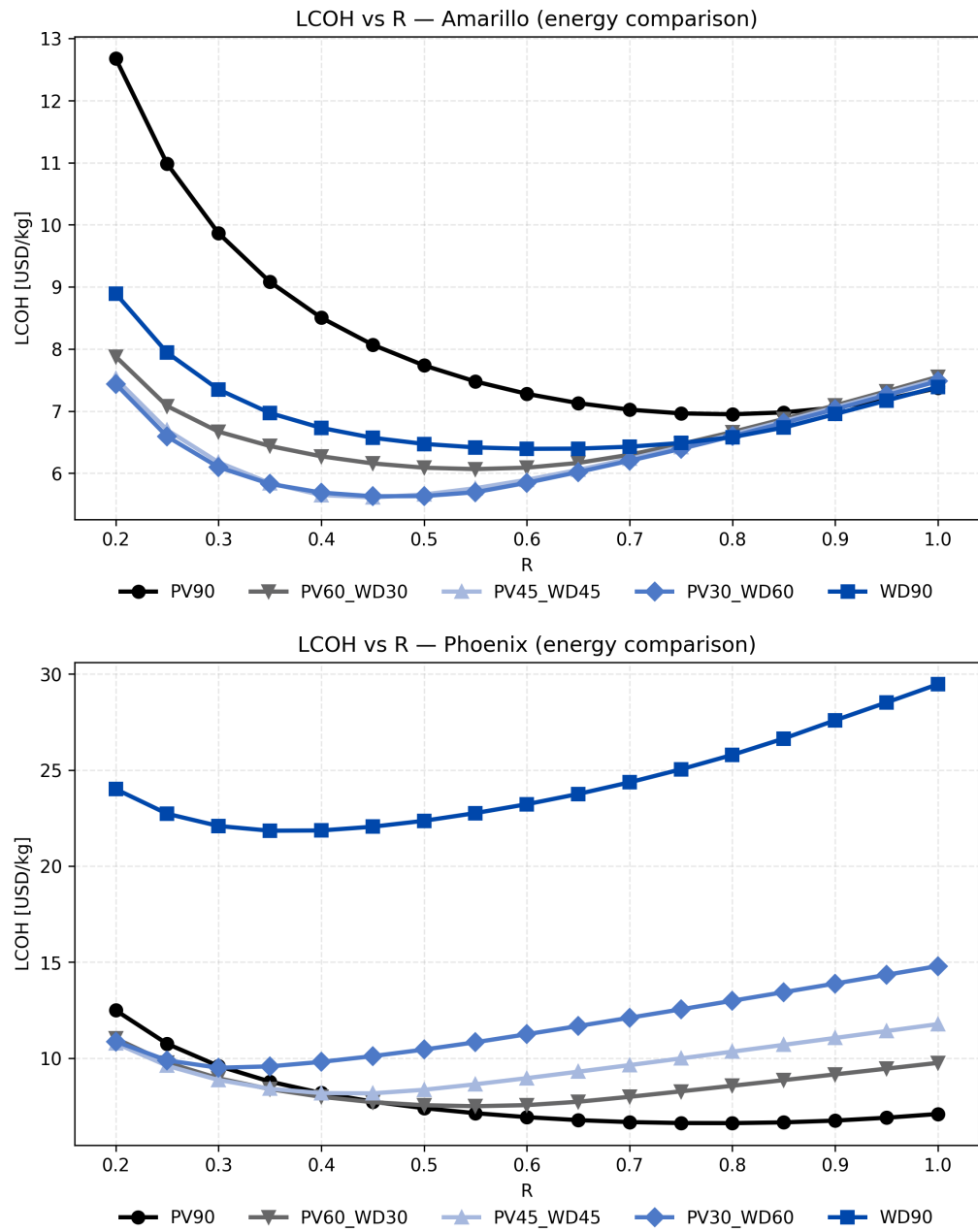


Figure 4.14: LCOH comparison across renewable configurations for Amarillo and Phoenix.

In Amarillo, hybrid PV-wind systems achieve lower LCOH due to complementary generation profiles and improved electrolyzer utilization. In contrast, in Phoenix, PV-dominant systems perform better due to strong solar resource availability and the limited contribution of wind.

Overall, these results demonstrate that optimal electrolyzer sizing depends not only on technology cost and efficiency, but also on the temporal characteristics of renewable resources. Therefore, optimal system design requires an integrated evaluation of techno-economic parameters and renewable variability.

4.4.3 Cost Breakdown Analysis

The cost structure of hydrogen production shows that energy is the dominant contributor to LCOH across all locations, followed by electrolyzer CAPEX, while water cost is negligible.

Figure 4.15 presents the cost breakdown for the optimal configuration at each location.

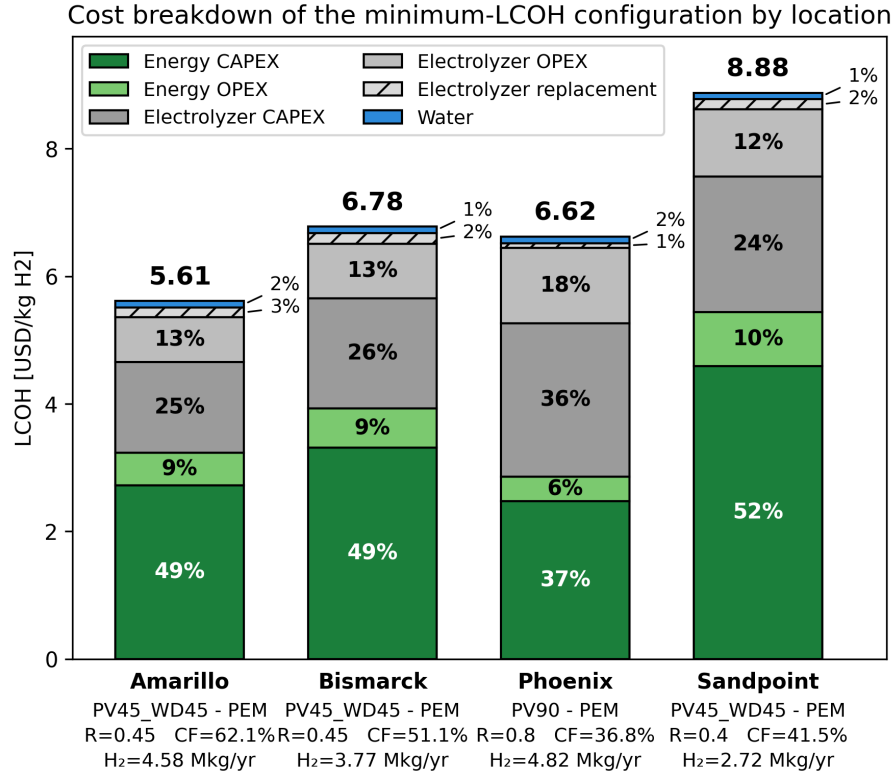


Figure 4.15: Cost breakdown of the optimal configuration for each selected location.

These results indicate that reducing renewable electricity cost and improving electrolyzer utilization are the most effective pathways for lowering LCOH. The following chapter explores the sensitivity of these results to key economic parameters.

Chapter 5

SENSITIVITY

The objective of this sensitivity analysis is to identify the main economic drivers affecting the Levelized Cost of Hydrogen (LCOH) and to determine the cost reductions required to achieve values below 2 USD/kg, a commonly referenced benchmark for green hydrogen competitiveness. In the United States, policy targets aim to accelerate cost reductions, including achieving hydrogen production costs below 2 USD/kg by 2026 under the Bipartisan Infrastructure Law and reaching 1 USD/kg by 2031 as part of the Hydrogen Shot initiative [9].

While the baseline analysis in Chapter 4 examined the influence of renewable configurations and operational parameters, this chapter focuses specifically on economic sensitivity, isolating the impact of cost reductions while keeping the technical configuration fixed. The analysis is based on the best-performing configuration for each location identified in the baseline study (Table 4.4).

The sensitivity analysis evaluates how reductions in technology costs affect LCOH and assesses the conditions required to approach competitive hydrogen production. Since only economic parameters are modified, technical outputs such as the optimal sizing ratio R , electrolyzer capacity factor, and hydrogen production remain unchanged.

5.1 Methodology and Results

A progressive cost-reduction approach was applied to evaluate the relative impact of the main cost drivers. In each case, a 66% reduction is applied to one additional parameter, while the others retain the reductions introduced in previous cases. This approach enables the evaluation of both the individual and cumulative contributions of each cost component to LCOH reduction.

Six sensitivity cases were evaluated based on the best-performing configuration in Amarillo:

- Case 1: Solar CAPEX reduction

- Case 2: Solar OPEX reduction
- Case 3: Wind CAPEX reduction
- Case 4: Wind OPEX reduction
- Case 5: Electrolyzer CAPEX reduction
- Case 6: Electrolyzer OPEX reduction

Because no technical parameter is modified, the optimal sizing ratio R , electrolyzer capacity factor, and hydrogen production remain unchanged throughout the analysis.

Group	Item	Base	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Solar	CapEx [USD/kW]	1432	-66%	-66%	-66%	-66%	-66%	-66%
	OpEx [USD/kW-y]	20.4		-66%	-66%	-66%	-66%	-66%
Wind	CapEx [USD/kW]	1537			-66%	-66%	-66%	-66%
	OpEx [USD/kW-y]	30.86				-66%	-66%	-66%
PEM	CapEx [USD/kW]	1627					-66%	-66%
	OpEx [USD/kW-y]	82						-66%
Results	LCOH [USD/kg]	5.61	4.76	4.62	3.69	3.50	2.46	2.00
	LCOH individual reduction [%]	0.0	15.2	2.3	16.6	3.5	18.4	8.2
	LCOH total reduction [%]	0.0	15.2	17.6	34.2	37.7	56.1	64.3

Table 5.1: Sensitivity analysis showing the progressive cost reductions required to reach an LCOH of 2 USD/kg.

The results show that capital cost reductions are the dominant drivers of LCOH reduction. Among the individual parameters, the largest effects are associated with solar wind and electrolyzer CAPEX, each contributing approximately 16-19% reduction in LCOH when introduced into the cumulative sequence. In contrast, operating cost reductions have a smaller impact, with solar OPEX contributing about 2-3%, wind OPEX about 4%, and electrolyzer OPEX about 8%.

These results indicate that CAPEX reductions provide significantly greater leverage for lowering hydrogen production cost than OPEX reductions. Under the cumulative 66% reduction pathway considered here, the baseline LCOH of 5.61 USD/kg is reduced to 2.00 USD/kg in Case 6, corresponding to a total reduction of 64.3%.

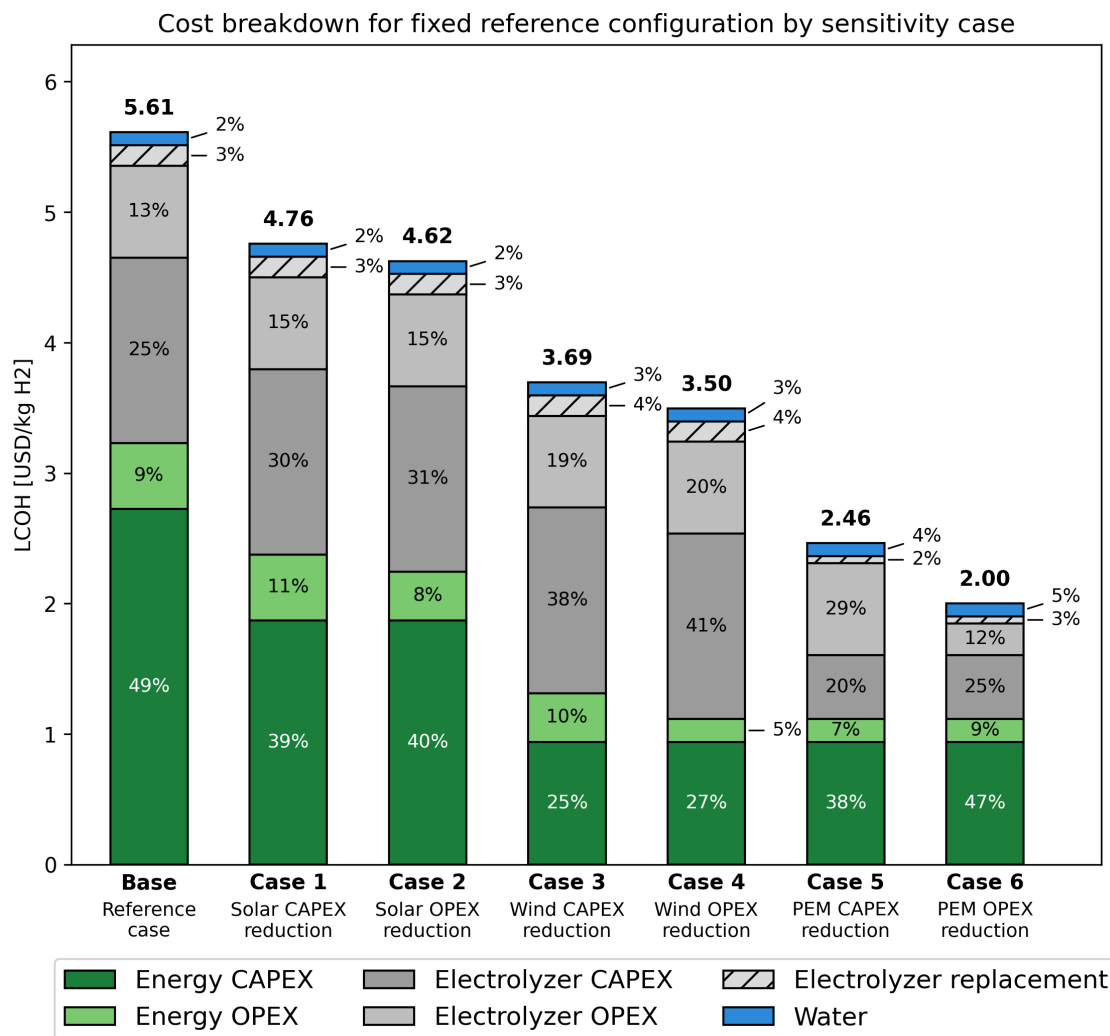


Figure 5.1: Evolution of the cost breakdown across cumulative sensitivity cases for the fixed Amarillo PV45-WD45 PEM configuration.

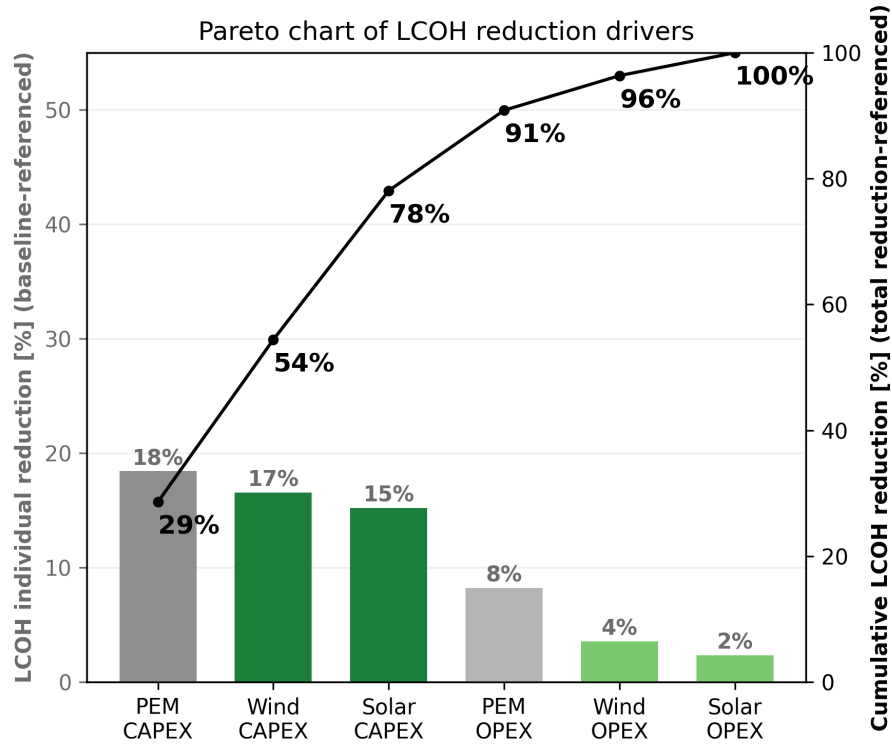


Figure 5.2: Relative contribution of the main cost drivers to LCOH reduction in the fixed baseline configuration.

The Pareto analysis indicates that the main contributors to LCOH reduction are PEM electrolyzer costs and renewable energy costs (solar and wind). Together, these components account for approximately 78% of the total LCOH reduction, while renewable energy costs alone contribute about 49%. This highlights the dominant influence of renewable generation and electrolyzer capital costs on the economic feasibility of green hydrogen production.

5.1.1 Extended Cost Reduction Scenario

Case 7 considers a more aggressive cost-reduction scenario than Case 6, with an 78% reduction applied to all cost components. This case is introduced to evaluate the level of cost reduction required for all selected locations to approach or fall below the 2 USD/kg threshold.

Under this scenario, Amarillo remains the best-performing location, achieving an LCOH of 1.29 USD/kg, while Sandpoint remains the most expensive, with an LCOH of 2.00 USD/kg. Compared with the baseline case, the spread between

locations is significantly reduced; however, the advantage of high-resource locations is not eliminated.

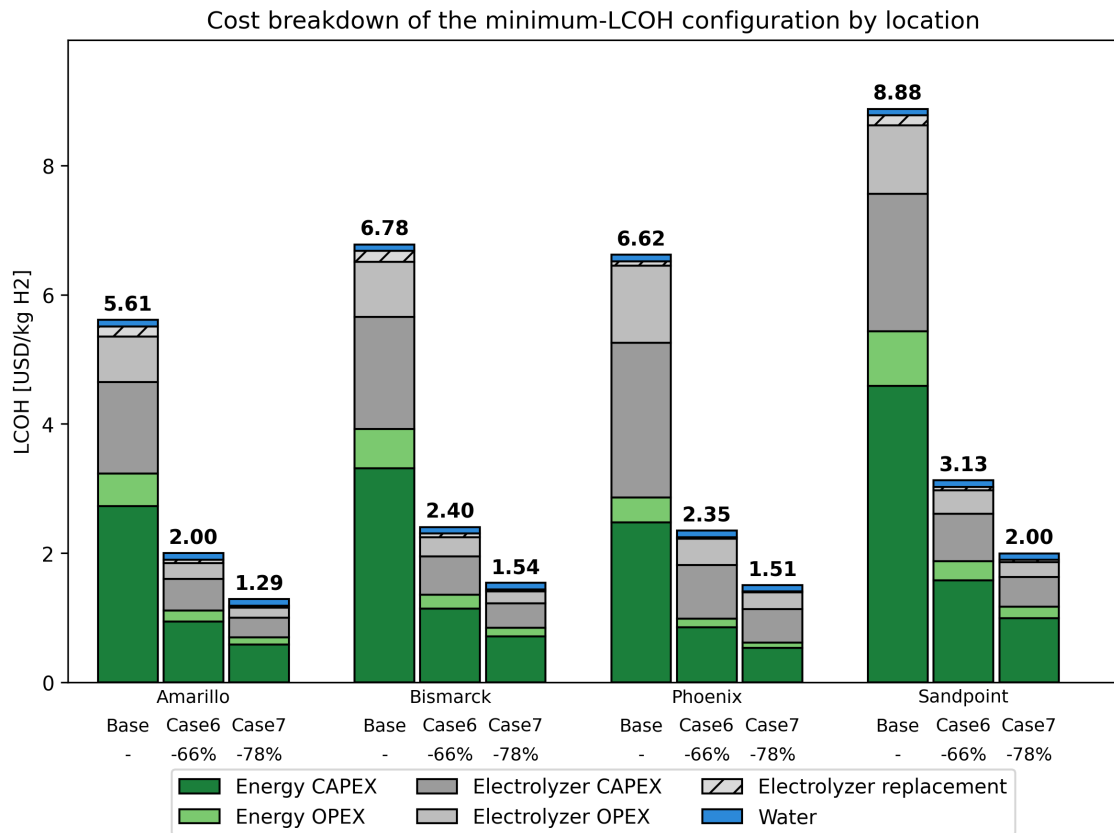


Figure 5.3: Comparison of minimum LCOH cost breakdowns across locations under the sensitivity cases.

These results indicate that, while technological cost reductions can substantially narrow regional cost differences, renewable resource quality remains a fundamental driver of hydrogen production cost.

Chapter 6

CONCLUSIONS AND FUTURE WORKS

This work presented a techno-economic analysis of green hydrogen production in off-grid renewable energy systems using hybrid solar and wind generation coupled with different electrolyzer technologies. The study evaluated how renewable resource variability, electrolyzer sizing, technology choice, and cost parameters influence hydrogen production and the Levelized Cost of Hydrogen (LCOH) across multiple geographic locations.

Key findings indicate that LCOH exhibits the characteristic convex relationship with the electrolyzer-to-renewable capacity ratio (R), confirming the existence of an optimal sizing point governed by the trade-off between electrolyzer utilization and renewable curtailment. At low values of R , high utilization is accompanied by significant curtailment, while at high values of R , curtailment decreases but electrolyzer utilization declines. These findings highlight electrolyzer sizing as a critical design optimization variable in renewable hydrogen systems.

The baseline analysis demonstrated that renewable resource quality is the dominant factor in determining hydrogen production cost. Among the selected locations, Amarillo achieved the lowest LCOH due to strong solar–wind complementarity, which effectively increases electrolyzer utilization. In contrast, lower-resource locations like Sandpoint showed significantly higher LCOH values, indicating that resource availability remains a structural determinant of project economics.

Consequently, hybrid PV–wind systems generally provided lower or more robust LCOH values than single-resource systems due to improved temporal distribution of generation and reduced intermittency. However, this benefit depends strongly on local resource conditions. In solar-dominant locations such as Phoenix, PV-only systems remain optimal, while in locations with stronger complementarity, hybrid configurations perform better.

Regarding electrolyzer technologies, PEM consistently achieved the lowest LCOH across baseline cases, with AWE showing comparable performance in several

scenarios. In comparison, SOEC resulted in higher LCOH due to its higher capital cost, shorter effective lifetime, and higher minimum operating load, which reduce operational flexibility under variable renewable supply.

The sensitivity analysis showed that capital cost reductions are the most influential drivers of LCOH reduction. Solar, wind, and electrolyzer CAPEX all produced significantly larger impacts than OPEX reductions. Under the cumulative 66% reduction pathway, LCOH decreased from 5.61 USD/kg to 2.00 USD/kg. While an aggressive 78% reduction scenario further reduced LCOH, it did not eliminate the economic advantage of high-resource sites. This indicates that cost reductions alone are insufficient, and that geography and renewable resource quality remain fundamental drivers of hydrogen economics.

The results suggest that cost-effective renewable hydrogen systems should prioritize appropriate electrolyzer sizing, hybrid renewable configurations where complementarity is available, and technologies with lower minimum load constraints and greater operational flexibility. These findings also indicate that improving electrolyzer flexibility may be as important as improving efficiency under variable renewable supply.

Limitations & Future Work

This study focuses exclusively on off-grid operation without grid interaction, battery storage, or electricity market participation. In addition, the economic assessment is limited to hydrogen production cost and does not account for policy incentives, tax credits, or additional revenue streams.

Future work should extend the present framework in several directions. Incorporating battery storage and grid-connected operation would enable the evaluation of their impact on renewable curtailment, electrolyzer utilization, and LCOH, as well as the potential benefits of electricity sales. Additional studies could also evaluate alternative AC/DC system configurations, including the use of DC PV systems without inverter stages and applying rectifier conversion only to wind generation.

Further analysis could include policy incentives, hydrogen compression and storage costs, and additional revenue pathways to assess system performance under more realistic deployment conditions. Future studies should also evaluate target LCOH values required for specific applications, such as distributed off-grid hydrogen production for transportation systems, including hydrogen storage requirements. In

this context, comparisons should be performed on an equivalent transportation metric (USD/mile) to provide a direct comparison between hydrogen and conventional fossil fuels, instead of evaluating systems on a USD/kg_{H₂} basis.

Overall, this work demonstrates that the economic viability of green hydrogen depends not only on cost reductions, but also on appropriate system design and renewable resource conditions. The results highlight the importance of integrated hourly techno-economic modeling for identifying cost-effective hydrogen production pathways and supporting the transition toward low-carbon energy systems.

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