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STOCHASTIC TECHNO-ECONOMIC FRAMEWORK FOR GREEN HYDROGEN PROJECTS UNDER UNCERTAINTY AND RISK CONDITIONS

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Final thesis submitted to the Electrical Engineering Graduate Program as one of the requirements to obtain the Ph.D. title in Electrical Engineering.

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ABSTRACT

This thesis presents a comprehensive stochastic techno-economic framework (STEF-H2V) for evaluating green hydrogen projects under uncertainty and risk conditions. Green hydrogen, produced through water electrolysis powered by renewable energy, is a promising solution for decarbonizing various sectors. The economic viability of green hydrogen investments is influenced by uncertainties and risks related to the environment, technological performance, financial parameters, and market dynamics. This research addresses these challenges by developing and applying a robust stochastic techno-economic framework (STEF-H2V) that integrates stochastic modeling techniques and advanced financial risk measures. The core of this thesis is the development of the STEF-H2V, a framework that employs Monte Carlo simulations to create a range of outcomes for key financial and operational parameters. This stochastic approach captures the inherent uncertainties in green hydrogen projects, providing a more realistic and robust assessment than deterministic methods. The framework incorporates financial risk measures, such as Value-at-Risk (VaR) and Omega ratio, to quantify potential financial losses and support better risk management. The framework structure includes methodological procedures, data collection, and investment analysis techniques. Applying the framework to a distributed green hydrogen generation case study shows its practical utility. The deterministic analysis provides a baseline understanding, while the stochastic analysis reveals the spectrum of outcomes, highlighting the importance of considering variability in financial and operational parameters. The VaR risk analysis shows how potential financial losses can be quantified and mitigated, offering a clearer picture of the project's risk profile. Further exploration of the gap in techno-economic analysis for green hydrogen investments by integrating financial risk management emphasizes the relevance of a holistic approach, including detailed evaluations of CAPEX, OPEX, and revenue streams. Incorporating financial risk measures leads to a more realistic project viability assessment, with sensitivity analysis identifying key drivers, such as electricity prices and technological efficiency. The framework's effectiveness under varying conditions of variability and uncertainty in hydrogen generation is also evaluated. This shows how fluctuations in key variables impact project feasibility, showing that the stochastic framework effectively captures the range of outcomes. The need for dynamic modeling approaches to adjust to changing conditions and provide more robust predictions is reinforced. The main findings of this research indicate that green hydrogen projects can achieve economic viability under favorable conditions despite high initial costs and technological uncertainties. Supportive policies and market mechanisms are crucial in reducing financial risks and encouraging investment. Integrating advanced risk measures and stochastic modeling techniques provides a comprehensive view of the financial landscape, enabling better risk management and decision-making. This document advances the green hydrogen investment analysis field by providing a detailed and adaptable framework for evaluating projects under uncertainty and risk conditions. By addressing the limitations of traditional approaches and incorporating advanced risk management techniques, STEF-H2V enhances the robustness and reliability of techno-economic evaluations, supporting the sustainable growth of the green hydrogen sector.

Keywords: green hydrogen, stochastic framework, techno-economic analysis, uncertainty and variability, financial risk, risk measures, Monte Carlo simulation, hydrogen investments.

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“I am stronger than myself.”

(Clarice Lispector)

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LIST OF ACRONYMS

2D	Two-Dimensional Monte Carlo Simulation
AEC	Alkaline Electrolytic Cells
BA	Bahia
BCR	Benefit-Cost Ratio
BoP	Balance of Plant
CAPEX	Capital Expenditures
CAPM	Capital Asset Pricing Model
CE	Ceará
CVaR	Conditional Value at Risk
EVA	Economic Value Added ® (a trademark of Stern Stewart & Co. → Stern Value Management (SVM))
EPBT	Energy Payback Time
EROI	Energy Return on Energy Invested
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse Gas
IRR	Internal Rate of Return
LCCA	Life-Cycle Cost Analysis
LCOE	Levelized Cost of Electricity
LCOH	Levelized Cost of Hydrogen
LHV	Lower Heating Value
MC	Monte Carlo
MCS	Monte Carlo Simulation
MG	Minas Gerais
MIRR	Modified Internal Rate of Return
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
ONS	National Electric Systems Operator
OPEX	Operational Expenditures
O&M	Operations and Maintenance
PB	Paraíba
PDF	Probability Density Function
PEM	Polymer Electrolyte Membrane
PE	Pernambuco
PI	Piauí
PV	Photovoltaic
QA	Quality Assessment
RES	Renewable Energy Sources
REPEX	Replacement Expenditure
RN	Rio Grande do Norte

ROI	Return on Investment
RQ	Research Question
RSL	Systematic Literature Review
SOEC	Solid Oxide Electrolytic Cells
SP	São Paulo
STEF-H2V	Stochastic Techno-Economic Framework for evaluating green hydrogen projects
TEA	Techno-Economic Analysis
TCO	Total Cost of Ownership
TLCC	Total Life-Cycle Cost
TOTEX	Total Expenditures
VaR	Value-at-Risk
WACC	Weighted Average Cost of Capital

NOMENCLATURE

Symbol	Description	Unit
WACC	Weighted Average Cost of Capital	%
k_d	Cost of Debt	%
k_e	Cost of Equity	%
D	Debt Ratio	%
E	Equity Ratio	%
τ	Income Tax Rate	%
ke	cost of equity	%
kd	cost of debt	%
rf	Risk-Free Rate	%
β	Beta Coefficient	-
rm	Market Return Rate	%
NPV	Net Present Value	$
CFn	Cash Flow at Time n	$
r	Discount Rate	%
t	Time Period	years
I0	Initial Investment Cost	$
OPEXn	Operating Expenditures at Time n	$
REVn	Revenue at Time n	$
LCOH	Levelized Cost of Hydrogen	$/kg
CAPEX	Capital Expenditures	$
OPEX	Operational Expenditures	$
REPEX	Replacement Expenditures	$
TOTEX	Total Expenditures	$
$LCO\tilde{H}$	Probability distribution for the LCOH	$/kg
$TOTE\tilde{X}$	Probability distribution for total cost values (TOTEX)	$
$GH\tilde{2}$	Probability distribution for green hydrogen production	kg
$\tilde{r}$	Probability density function assigned to the discount rate	%
m_{H2}	Mass of green hydrogen production	kg
$mH\tilde{2}$	Probability distribution for green hydrogen production	kg
$\tilde{\imath}$	Probability distribution of the WACC (interest rate)	%
$PVeg$	PV electricity generation	kW
η	PV cells efficiency	%
ρ	Local irradiation	kWh/m2
A	Occupation area by the system	m^2
δ	PV degradation factor	%
γ	PV system losses	%
G_{H2}	Hydrogen Production	kg
P_{El}	Power Input to Electrolyzer	kW
u	Utilization Factor	%
E_{El}	Electricity consumption of the electrolyzer	kWh/kg
δ	PEM system degradation rate	%
VaR	Value at Risk	$/kg
α	Confidence Level	%
W*	Minimum value for w	$/kg
f(w)	probability distribution function for w	

CVaR	Conditional Value at Risk	$/kg
σ	Standard Deviation	-
μ	Mean	-
PDF	Probability Density Function	-
CDF	Cumulative Distribution Function	-
Ω	Omega Ratio	-
L	Threshold Value	$/kg
I1	Weighted Earnings Average Below L	-
I2	Weighted Earnings Average Above L	-
F(x)	Cumulative Probability Distribution of Returns x	-
a	Maximum Value in a Cumulative Distribution	$/kg
b	Minimum Value in a Cumulative Distribution	$/kg
ρ	Correlation Coefficient	-

1. INTRODUCTION

1.1 Context setting and motivation

Greenhouse gas emissions have caused severe changes in ecosystems and intensified climate change. Renewable Energy Sources (RES) have become crucial for supplying more sustainable energy, ensuring nations' well-being and socioeconomic progress. Such sources as solar, wind, and biomass play a fundamental role in resolving and mitigating the environmental impacts caused by humans on Earth. Industrialized countries worldwide have developed policies to increase the insertion of renewable sources in their electrical and energy matrices.

In power generation from renewable sources, it is essential to underscore these sources' substantial climatic dependency and intermittent behavior, rendering wind and solar photovoltaic energy as non-dispatchable sources. This dependency results in the instability of electrical systems and unbalances between supply and demand, creating an opportunity for dialogue regarding energy storage systems [1], [2], [3]. If, on one hand, the generation of renewable electricity presents a high sign of intermittence, on the other hand, the continuous use of fossil fuels should be highlighted as a real threat to the environment.

The extreme volatility of oil prices (the war between Russia and Ukraine shows it) is also emphasized by the increasing CO_2 emissions by industry and transportation. These two narratives above have opened a space for the hydrogen economy, which is at a crucial point as an essential strategy for transport and energy storage [4], [5]. The hydrogen economy has the potential to boost the system's decarbonization, fully exploiting the benefits associated with renewable energies and bypassing the harmful effects of the use of fossil fuels on transportation and other end-use applications in which carbon is released into the atmosphere [6], [7].

Green Hydrogen is produced by water electrolysis without the emission of greenhouse gases if the electricity used for processing comes entirely from renewable sources, such as wind and solar [8]. Green hydrogen is a decarbonization vector that is used in several processes. As a chemical raw material, it can provide a basis for chemicals such as methanol and ammonia [9], [10]. If used as fuel, it becomes a decarbonization vector for all non-electric end uses [11]. When burned, it will substantially reduce CO_2 emissions and air pollution [11], [12]. If used by electric fuel cell vehicles (FCEVs), it can halve transport energy requirements, eliminating pollution without compromising vehicle autonomy [11], [13]. It can also be used as energy storage to smooth intermittences of renewable generation, for load shifting or peak shaving, improve energy efficiency, enable new smart electricity markets, and provide resilience to the whole energy system [14], [15], [16]. Therefore, green hydrogen and renewable electricity might be the key to a carbon-neutral energy system for all people's environments [6], [7].

Brazil does not yet have a commercial generation of green hydrogen. Research on green hydrogen in Brazil is early, with published literature still under development [17] as demonstrated by a bibliometric analysis of reliable Brazilian news sources and central databases (e.g., Scopus, Web of Science, ScienceDirect, IEEEXplore, Google Scholar, and the “Portal de Periódicos da CAPES” in Portuguese). The search was conducted over the last five years using the keywords hydrogen, green hydrogen, and Brazil, both in Portuguese; Boolean operators were also used to scan as many documents as possible in the area. Table 1.1 presents the survey results with the substantial green hydrogen initiatives in the country, and Fig. 1.1 shows the state’s distribution of the documents analyzed.

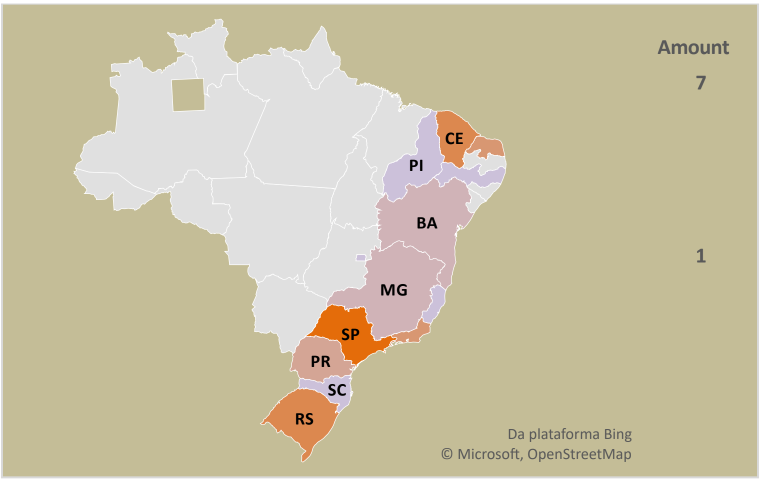

Fig. 1.1. Distribution of bibliometric analysis on green hydrogen in Brazil.

By examining Fig. 1.1 and Table 1.1, most projects, studies, and applications in green hydrogen are concentrated along the coastal states of Brazil. One explanation is that the northeast and Brazilian coasts have the most significant electricity production through wind and solar PV generation [18], [19]. Therefore, it is possible to say that the country’s vast majority of green hydrogen projects were concentrated in these states. In addition, it is also essential to highlight the gas pipeline grid in the country, which is concentrated in the areas highlighted on the map [20], further reinforcing the narrative that the hydrogen infrastructure will develop in these regions.

The data presented shows the maturity level of Brazil’s green hydrogen sector. Regarding the techno-economic issue, the literature is even more limited. Only six documents of the consulted literature deal with the subject, and when analyzing them, it was found that all works used a deterministic approach for technical and economic analysis. This reality is not so distant from the international literature, especially regarding technical-economic studies encompassing risk and uncertainty.

TABLE 1.1. BRAZILIAN LITERATURE ABOUT GREEN HYDROGEN.

Subject / Application	**Scale**	**Year**	**Source**
Environmentally Sustainable Green Hydrogen Production	Lab	2022	[21]
Levelized Cost of Hydrogen from Off-Grid PV Plants	Large	2022	[22]
Green Hydrogen Portal – iHBrasil	Large	2022	[23]
Large-Scale Maritime Transport of Hydrogen	Large	2022	[24]
Green Hydrogen: Challenges for Chemistry	-	2022	[25]
Solution-Based Techniques for Green Hydrogen Production	Lab	2022	[26]
Platinum Weight Influence on Green Hydrogen Production	Lab	2022	[27]
Geographical Implications of the Green Hydrogen Sector	-	2022	[28]
Pathways for Oil and Gas Companies Towards a Sustainable Future	Large	2022	[29]
Wind and Solar PV for Hydrogen Production and Storage	Large	2022	[30]
Research-to-business new Opportunities on Green Hydrogen	-	2022	[31]
Green Hydrogen Pilot Plant at Açu Port	Large	2022	[32]
GIZ’s H2l Project – Federal University of Santa Catarina	Small	2022	[33]
GIZ’s H2Brasil Project – Federal University of Itajubá	Small	2021	[34]
Green Hydrogen Hub - Ceará	Large	2021	[35]
Green Hydrogen and Offshore Wind - Rio Grande do Norte	Large	2021	[36]
Piauí R&D Pilot Project	Large	2021	[37]
Pilot Project – Neoenergia and Government of Pernambuco	Large	2021	[38]
Hydrogen: Current Advances and Patented Technologies	-	2021	[39]
Carbon-neutral Maritime Fuels Production	Lab	2021	[40]
Processes of Hydrogen Production and Challenges by 2050	-	2021	[41]
Biomethane and Hydrogen from the Wine Industry	Industrial	2021	[42]
Fuel Cells Transforming Biogas into Hydrogen and Electricity	Lab	2021	[43]
Green Hydrogen Generation Plant - FURNAS	Small	2021	[44]
Green Hydrogen Production and Offshore Wind Energy	Large	2021	[45]
Biomethane and Biohydrogen from Ethanol Plants’ Waste	Large	2021	[46]
Hydrogen Regulation	-	2020	[47]
Solar-wind Hydrogen to Produce Nitrogen Fertilizers	Small	2020	[48]
Green Hydrogen Production and Storage for Public Transport	-	2020	[49]
Solar-powered Hydrogen Refueling Stations	Small	2020	[50]
The Surplus of Wind Farms for Hydrogen and Electricity	Large	2020	[51]
Hydroelectric and Wind Farm Surplus Energy	Large	2020	[52]
Hydrogen Bio-production Brewery Wastewater	Lab	2019	[53]
Hydrogen-syngas and Biogas from Rice Parboiling Industries	Industrial	2019	[54]
Hydrogen Productive Chain	-	2019	[55]
Energy Storage Project São Paulo - CESP	Small	2019	[56]
Production of Biohydrogen from Brewery Wastewater	Lab	2018	[57]

This study centers on hydrogen production utilizing PEM (Proton Exchange Membrane) electrolysis technology powered by onshore wind and solar photovoltaic resources, whether distributed or at a utility-scale. The methodology outlined in this thesis aims to provide stakeholders in investment, policymaking, and government with a comprehensive and resilient framework for evaluating and economically comparing investment scenarios in green hydrogen initiatives.

1.2 Objectives

This thesis aims to develop a stochastic framework for techno-economic analysis (TEA) under uncertainty and risk conditions to manage the financial risk in green hydrogen investments in Brazil. The specific objectives are described below through an adaptation of Bloom's taxonomy for the cumulative process in order to support the classification of each objective [58]:

- Explore TEA initiatives in green hydrogen investments in Brazil, Germany, and the United States.
- Examine and systematize models and tools applied to TEA regarding design assumptions, operating mechanisms, and data structuring (H2A, H2FAST, H2A-Lite).
- Develop the stochastic framework (STEF-H2V).
- Define the uncertainties, variability, and risk measures to be applied in the framework.
- Employ the developed framework and execute a performance evaluation in case studies.

1.3 Justification and Contributions

The expected results will deliver a comprehensive view and the potential to employ a stochastic techno-economic framework (STEF-H2V) for assessing investments in green hydrogen within uncertainty, variability, and risky contexts. Furthermore, by providing a performance evaluation and conducting a sensitivity analysis, the results should address the existing research gap and serve as a valuable reference for project selection and development in the respective field.

The research is valuable as it fills a gap in the existing literature by adopting a holistic approach in this specific field of application. Subsequently, the study shows a stochastic approach for analyzing investments in green hydrogen, incorporating financial indicators, risk assessment, and uncertainties. This study provides a valuable point of reference for future undertakings. Using a stochastic approach via Monte Carlo simulation further enables the exploration of optimization tools in investment analysis. A significant breakthrough has been achieved in research, as a proposal has been made to apply a comprehensive methodology that aligns with current best practices, guaranteeing the reproducibility of the findings.

The journal-published paper related to this Ph.D. thesis is [236]:

Andrade J.V.B. de, Costa V.B.F. da, Bonatto B.D., Áquila G., Pamplona E. de O., Bhandari R. **Perspective under uncertainty and risk in green hydrogen investments: A stochastic approach using**

Monte Carlo simulation. International Journal of Hydrogen Energy 2023. https://doi.org/10.1016/J.IJHYDENE.2023.08.253 .

1.4 Thesis layout

This thesis is structured into eight chapters. **Chapter 1** presents the introduction, justification, and main contributions. **Chapter 2** introduces the theoretical concepts and literature relevant to the study. It covers topics such as green hydrogen production, financial indicators for investment analysis, and stochastic modeling techniques. This chapter also includes a systematic literature review to identify current practices and gaps in green hydrogen investment analysis, emphasizing the need for advanced risk assessment tools and stochastic methods. **Chapter 3** introduces the core framework developed in the thesis. It details the methodological procedures, data collection processes, and investment analysis techniques used in STEF-H2V. The framework's structure, adaptability to different regions, and ability to incorporate emerging technologies are also discussed, showcasing its robustness and flexibility in evaluating green hydrogen projects under uncertainty and risk conditions.

Chapter 4, the STEF-H2V, is applied to a distributed green hydrogen generation case study. The deterministic analysis provides a baseline understanding, while the stochastic analysis reveals a spectrum of outcomes. This chapter emphasizes the importance of considering variability in financial and operational parameters and shows how Value-at-Risk (VaR) can quantify and mitigate potential financial losses, offering a more precise project risk profile. An extension of the framework is presented in **Chapter 5** to explore the integration of financial risk management into green hydrogen investments. It underlines the value of a holistic approach. The case study illustrates how incorporating financial risk measures leads to a more realistic assessment of project viability, with sensitivity analysis identifying key drivers, such as inflation rate and utilization. **Chapter 6** examines the framework's effectiveness under conditions of variability and uncertainty in hydrogen generation using 2D simulation. The case study evaluates the impact of fluctuations in key variables on project feasibility, demonstrating that the stochastic framework effectively captures the range of outcomes. The chapter reinforces the need for dynamic modeling approaches to adjust to changing conditions and provide more robust predictions.

Chapter 7 discusses the limitations of the research, such as data availability, model assumptions, and regional specificity. It highlights the framework's extensibility, suggesting potential areas for future research, including enhanced data collection, dynamic and adaptive modeling, and policy and market analysis. The chapter emphasizes the value of addressing these limitations to improve the robustness and applicability of the framework. The **final Chapter (8)** summarizes the main findings of the thesis, highlighting the contributions made to the green hydrogen investment analysis field. It reiterates the significance of incorporating stochastic modeling and advanced risk measures in techno-economic evaluations. The chapter concludes by emphasizing the potential of green hydrogen projects to achieve economic viability under favorable conditions and the importance of supportive policies and market mechanisms in reducing financial risks and encouraging investment.

2. THEORETICAL BACKGROUND

2.1 Green hydrogen

Climate change is imposing significant changes and challenges to the current energy system. The continuous increase in the use of Renewable Energy Sources (RES) worldwide has been observed over the last few decades. Using energy-efficient technologies combined with RES can potentially reduce greenhouse gas (GHG) emissions and air pollution. It is in this context that green hydrogen is inserted because, like electricity, hydrogen is a secondary energy carrier, an energy vector, and can convert, store, and release energy through the production of electricity from variable sources such as wind power and photovoltaics, making it a long-term storage option for excess renewable electricity.

According to IRENA [59], hydrogen could contribute 10% of the mitigation targets required to reach net zero by 2050 in a 1.5°C scenario and 12% of the final energy demand. Today, global hydrogen production is around 75 Mt/year as pure hydrogen (an additional 45 Mt/year as part of a gas mixture), equivalent to 3% of the global final energy demand [59].

As mentioned, green hydrogen is a versatile energy carrier (See Fig. 2.1). It can be produced from renewable electricity by electrolysis of water, coupling the continuous increase in renewable energy with the end-uses of difficult electrification. Such coupling also increases electricity flexibility by connecting electrolyzers to the electrical grid, making the grid smart, which can be complemented by alternatives such as batteries, demand response, charging stations, and electric vehicles for a more resilient grid.

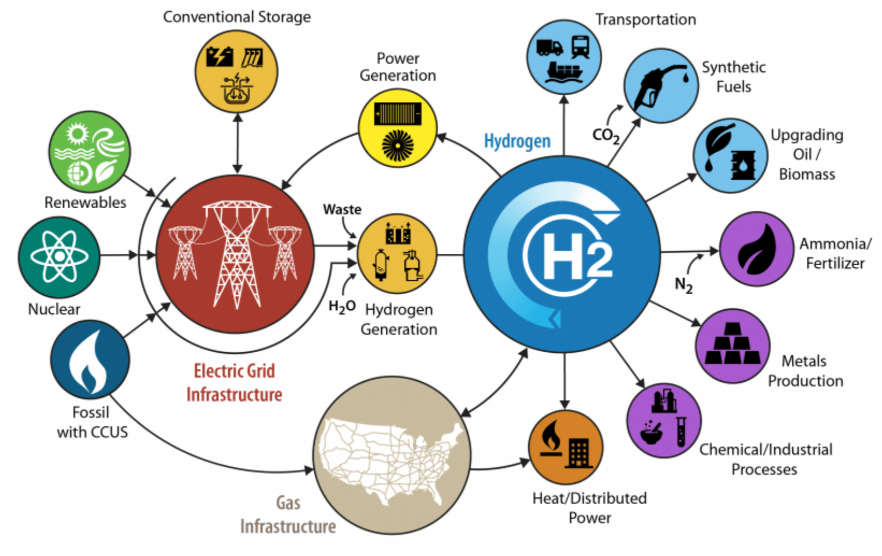

Fig. 2.1. Green hydrogen production, conversion, and end-use across the energy system.

Source: [60].

In 2021, approximately 47% of the world's hydrogen production came from natural gas, 27% from coal, 22% from oil (as a by-product), and only nearly 4% from electrolysis (resulting in a total capacity of 0.7 GW) [59]. Even though electricity had a global average renewable share of approximately 33% in 2021, green hydrogen production accounted for only almost 1% of global hydrogen production [59]. This difference is because not all electricity used for water electrolysis comes from renewable sources, which characterize green hydrogen.

This subject opens space for dialogue about the production potential of green hydrogen and discusses the colors of hydrogen resulting from the different production processes and sources. After all, what is green hydrogen, and what colors can hydrogen have? The idea of classifying hydrogen according to its production method and the type of energy used has become popular, as they relate the different costs of hydrogen and emissions in production processes. In this way, hydrogen generation technologies are often classified based on different colors, for example, gray, blue, green, and yellow (see Fig. 2.2).

	Black	Brown	Grey	Blue	Turquoise	Yellow	Pink	Mossy	Green
Technology	Gasification	Gasification	Natural gas reforming	Natural gas reforming	Pyrolysis	Water electrolysis	Water electrolysis	Gasification or anaerobic digestion	Water electrolysis
Source	Black Coal (anthracite)	Brown Coal (lignite)	Natural Gas	Natural Gas or coal (+ CCS)	Natural Gas or methane	Grid electricity	Nuclear energy	Biomass or biofuels	Renewable Energy
Footprint	High	High	Medium	Low	Solid carbon (by-product)	Low / Medium	Minimal	Minimal	Minimal

Fig. 2.2. Classification of hydrogen in a color scale.

Source: Elaborated from [61], [62], [63], [64].

In Brazil, hydrogen production is concentrated in the refining and fertilizer sectors, which use production processes with high CO_2 emissions [65]. Following the world trend, hydrogen production in Brazil also occurs by reforming natural gas (gray hydrogen) with plants installed primarily in coastal regions because of the Brazilian gas pipeline network [62]. In the last two years, much has been discussed about the Brazilian potential for the production of green hydrogen, with an emphasis on wind and solar energy in the electrolysis process and biomass. Brazil has great potential for renewable sources, which directly contribute to the production of green hydrogen.

Since 2021, several events, such as workshops and seminars, have occurred in Brazil to host dialogues on the production of green hydrogen in the country, involving governments, academia, industry, and market agents (see Table 1.1). Debates about the importance of a national hydrogen program, the hydrogen economy, and green hydrogen production have heated the national scene, centering discussions on structuring a new and potential market.

Brazil has five main sectors as a hydrogen consumer market [65]: petrochemicals, for fuel refining; steel and metallurgy, for the reduction of pig iron and controlling atmosphere in furnaces; food, for the hydrogenation of products, mainly margarine; flat glass, for the process of inserting the tin bath, in order to prevent the formation of defects in the glass and protect the chambers/equipment in which the glass is formed; and power generation (thermoelectric) for cooling turbines. In addition, the transport sector stands out, including cars, buses, planes, and ships.

2.2 Financial indicators

- Weighted Average Cost of Capital (WACC)

Weighted Average Cost of Capital (WACC) provides a comprehensive measure of the cost of interest-bearing liabilities and equity that are consistently used in an investment. Utilizing the WACC method to estimate a discount rate is a prevalent approach in the literature concerning investment analysis in renewable energy [66], [67]. When evaluating private investments, such as the feasibility of investing in a renewable source project, one crucial factor to consider is the cost of financing, commonly known as the WACC [68]. In short, the WACC is a broader indicator of a company’s cost of funds, representing the return a company must earn for investors to buy its common stock, preferred stock, and bonds [69]. The WACC is calculated as a function of the company’s cost of equity (ke) and the cost of debt (kd), both expressed as a percentage, represented by Eq. (2.1):

$$WACC = k_d D(1-\tau) + k_e E \tag{2.1}$$

D is the debt ratio, E is the equity ratio, and τ is the income tax rate.

The debt/equity ratio characterizes the investor’s capital structure, where the cost of debt is represented by the average cost of financing raised in the market. Interest-bearing liabilities are considered the book value of debt, and the cost of equity is estimated using the Capital Asset Pricing Model (CAPM).

- Capital Asset Pricing Model (CAPM)

The CAPM, proposed by Sharpe [70], is widely used to estimate the cost of equity, explaining the relationship between risk and the rate of return demanded by the investor, and has also been used in renewable energy investments [67], [68], [71], [72]. The CAPM is illustrated in Eq. (2.2):

$$k_e = r_f + \beta * \left(r_m - r_f\right) \tag{2.2}$$

In Eq. (2.2), r_f represents the risk-free rate (%); β is the asset risk concerning the market, and (r_m – r_f) means the market risk premium (%).

It is essential to highlight that the CAPM considers the proportional variation of the risk premium in a competitive market, influenced by non-diversifiable risk factors, such as political scenarios, recessions, and capital flight. These factors are represented by the beta, along with the market's expected risk premium and the theoretically risk-free return [71]. Additionally, it is crucial to note that in the CAPM model, beta (β) serves as a quantification of systematic risk, specifically market risk rather than individual stock risk, which cannot be mitigated within a particular market, referred to as the "risk of the whole economy" [73]. In contrast, there is an unsystematic risk, which is the company-specific risk (not market risk) and can be avoided with diversification, viz., diversified stocks [73]. Therefore, β only captures systematic risk in the CAPM model since an investor is assumed to be well-diversified [73].

- Net Present Value (NPV)

The NPV is centered on the present value of each future cash flow (negative and positive) generated over the project's lifetime. Hence, it is calculated as the sum of discounted net cash flows:

$$NPV = \sum_{n=0}^{N} \frac{CF_n}{(1+r)^n} = \sum_{n=1}^{N} \frac{CF_n}{(1+r)^n} - I_0 \qquad (2.3)$$

where CF is the net cash flow at time n, r is the discount rate based on WACC and/or CAPM, n is the number of periods, and I_0 is the initial investment cost (CAPEX).

If one has an NPV > 0, revenues are more significant than costs, and investment is profitable. Projects with a higher NPV are better if one wants to evaluate or choose between mutually exclusive projects [74]. NPV can be rewritten in terms of CAPEX and OPEX, distinguishing costs and revenues:

$$NPV = -CAPEX_T - \sum_{n=1}^{N} \frac{OPEX_n}{(1+r)^n} + \sum_{n=1}^{N} \frac{REV_n}{(1+r)^n} \qquad (2.4)$$

where REVn is the annual revenue obtained by the project in year n, OPEX is the operating expenses (fixed and variable O&M costs) in year n, and CAPEX is the investment cost.

- Levelized Cost of Hydrogen (LCOH)

The cost of green hydrogen can be estimated by considering the levelized cost of hydrogen. The calculation of LCOH includes the initial investment required for plant construction and the management costs incurred over its entire useful life. This metric can exhibit substantial fluctuations, contingent upon variables like plant size and the primary energy source used for production [75].

LCOH can be represented as a function of capital costs, fixed and variable costs of operation and maintenance annualized by a capital recovery factor. The sum of these costs in \$/year is divided by the annual hydrogen production rate in kg/year (also annualized by a discount rate), thus quantifying LCOH in units of \$/kg. Under the previous description, the LCOH was calculated in (2.5):

$$LCOH = \frac{CAPEX_T + \sum_{n=1}^{N} \frac{OPEX_n}{(1+r)^n}}{\sum_{n=1}^{N} \frac{G_{H2}}{(1+r)^n}} \tag{2.5}$$

where: $CAPEX_T$ = Capital expenditures of the investment (\$); OPEXn = operational expenditures of the investment (\$); r = discount rate (%); GH2 = green hydrogen production (kg).

From Eq. (2.5), it is possible to infer that the LCOH is equal to the ratio among the present value of the sum of all costs during the project lifetime to the present value of hydrogen production, i.e., as discounted cash flows divided by the discount hydrogen output [76]. Subsequently, it becomes workable to delineate Eq. (2.5) in detail:

$$LCOH = \frac{TOTEX_T}{\sum_{n=1}^{N} \frac{G_{H2}}{(1+r)^n}} = \frac{Total\ Lifetime\ Cost}{Total\ Lifetime\ Hydrogen} \tag{2.6}$$

where: $TOTEX_T$ = the total costs that result from the sum of CAPEX and discounted OPEX (US\$).

LCOH considers not only the initial investment because of the plant's construction but also all the management costs over the entire useful life (TOTEX), which can also include replacement and decommission expenditure and can vary significantly depending on the plant's size and the primary energy sources for its production [75]. The LCOH is an efficient financial indicator for measuring the economics and competitiveness of different hydrogen production processes [77].

The LCOH is based on the same principles as the Levelized Cost of Energy, calculated by dividing the discounted total of costs by the discounted total of energy production [78]. According to the Department for Energy Security and Net Zero in the UK, this approach considers that when the net present value (NPV) of a project is zero, the internal rate of return (IRR) of the project is equal to its discount rate, where NPVproject = NPVrevenues - NPVcosts = 0 [79]. In the case of LCOH, the methodology is applied to the discounted sum of generated hydrogen, referred to as the net present hydrogen (NPH). The levelized cost of a hydrogen production technology in this document is understood as the ratio between the total costs of a generic plant and the total amount of hydrogen expected to be produced over the plant's useful life. Both are expressed in net present value, meaning that future costs and outputs are discounted compared to current costs and outputs [78], [79].

Reducing LCOH is essential to green hydrogen adoption, which can be achieved either by decreasing the magnitude of terms in the numerator (i.e., reducing costs) or by increasing annual hydrogen production in the denominator of Eq. (2.5) (for example, through efficiency increases) [80]. Each term in Eq. (2.6) is a part of a coupled system, with changes to one value impacting other terms.

- Value-at-Risk (VaR)

In risk management, VaR is a widely used measure [81], [82]. VaR seeks to answer what is the worst value that an investor can expect with a certain probability of loss at a specified confidence interval (α confidence level) within a time horizon, described by Eq. (2.7) [67], [82]:

$$1-\alpha=\int_{-\infty}^{W^*} f(w)\,dw=P(w\le W^*)=p \tag{2.7}$$

where: α = confidence level; W* = minimum value for w; f(w) = probability distribution function for w.

Because VaR forecasts are easy to understand, they help risk managers assess their exposure to significant unexpected losses and mitigate the general risk of financial markets [67], [81].

- Conditional Value at Risk (CVaR)

VaR originated the CVaR, defined as the expected value of losses that exceed VaR, i.e., losses greater than or equal to VaR [67]. Unlike VaR, CVaR is a more pessimistic measure, is described as the upper limit for the maximum acceptable loss, and can identify catastrophic events within a data distribution [67], [83]. In Eq. (2.8), a basic CVaR calculation equation is explained mathematically [67]:

$$CVaR(w)=\int_{VaR(w)}^{\infty} z\frac{fw(z)}{1-\alpha}dz \tag{2.8}$$

The main difference between CVaR and VaR measurements is that VaR is related to the probability of excess loss, while CVaR is related to the expectation of excess loss (as shown in Fig. 2.3) [67], [84]. Despite this, when evaluated in combination, VaR and CVaR offer a comprehensive understanding of the risk associated with a particular distribution.

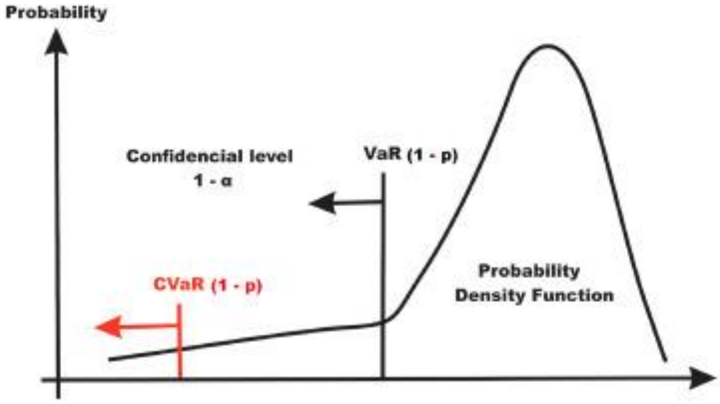

Fig. 2.3. VaR and CVaR representation.

Source: Adapted from [67].

- Omega ratio (Ω)

Another unknown financial indicator associated with risk in the literature for analyzing the performance of energy and hydrogen systems investment is the Omega ratio (Ω), presented by Keating and Shadwick [85]. The relation between the financial gains or returns of the investment over a threshold loss or threshold value (L) and the loss values is determined by the Omega ratio. [86], [87]. The measure focuses on the potential downside and upside gains, as it represents the ratio of the expected return on a call option and the expected return on a put option with the same exercise and underlying contingent claim [88]. The Omega function can be described mathematically continuously, in Eq. (2.9):

$$\Omega\,(L) = \frac{I_2}{I_1} = \frac{\int_L^b [1 - F(x)]dx}{\int_a^L F(x)dx} \tag{2.9}$$

where: F (x) = probability density function (PDF) of returns x; L = threshold value; b = maximum value in a cumulative distribution, and a = minimum value in a cumulative distribution.

The Ω is simple calculated from a mathematical point of view and overcomes the limitation imposed by the assumption of normality of the distribution when comparing investment alternatives based on the chances of profit above a particular target [87], [88], [89]. The Ω calculation represents the ratio between the area of values more significant than the L value divided by the area of the lower values. Fig. 2.4 facilitates the interpretation of Eq. (2.9).

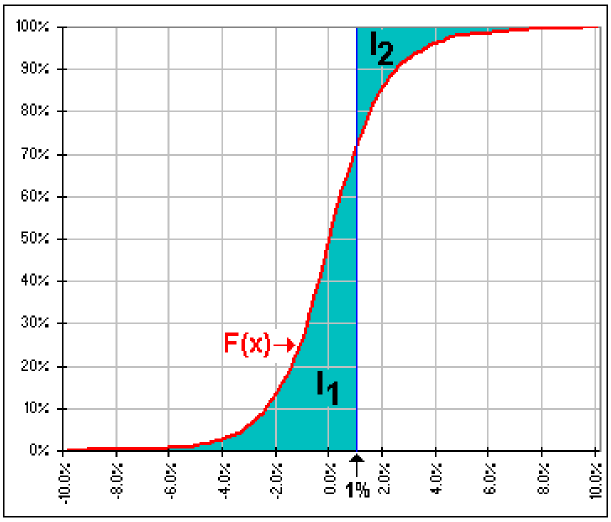

Fig. 2.4. Limit of the gains and losses.

Source: [90].

Ω is calculated by dividing the I2 area above the L value by the I1 area below the L value. Therefore, it is defined that [91]:

- (a,b) is the lower and upper bounds of the distribution's range of returns. In the most general case, a = - ∞ and b = ∞.
- $I_2(L)$ is the weighted earnings average above the L level (upper area of Fig. 2.4).
- $I_1(L)$ is the weighted earnings average below the L level (bottom area of Fig. 2.4).
- F(x) is the return's cumulative probability distribution.

2.3 Monte Carlo Simulation

The Monte Carlo (MC) method originated in Los Alamos during the 1940s, when physicists addressing particle transport issues began employing the Monte Carlo method [92]. The exact etymology of the name varies across different sources. However, there is a consensus that it is connected to the gambling activities in the casinos of Monte Carlo [93]. The first revolutionary step introduced at this time was using (pseudo) random number generators in place of physical experiments to perform the calculation; the second was the realization that it is unnecessary to use collections of independent random variables of known distribution [92].

The MC method is robust for simulating stochastic phenomena and can provide a realistic view of energy systems' technical-economic and operational performance, considering uncertainties, which are highly relevant but neglected in deterministic models [94], [95], [96], [97], [98], [99], [100], [101]. By using random numbers, the MC simulation estimates various functions of a probability distribution to solve the problem, specifically by estimating the expected value using a simulated sample of the distribution of the random variable [102]. The MC simulation becomes a powerful tool for simulation in technical-economic studies aligned with risk measures and uncertainties [67], [83], [87], [103].

MC simulations provide probability distributions of the output variables that might investigate uncertainty, risks, and disadvantageous scenarios for investment projects with more sophisticated metrics [67], [87]. The literature presents some risk measures based on the potential loss of financial management. Based on the specific risk profile of a particular asset or investment, risk measures can be applied using stochastic theory to evaluate energy projects [81], [82], [83], [84], [87], [104]. One of the software for MC simulation/analysis is *Crystal Ball*®, which was used in this study. The tool uses tornado and life analysis in hyper-acute sampling and stochastic risk analysis and is a good ally for investment analysis and decision-making processes.

2.4 2D Simulation

Two-dimensional Monte Carlo Simulation, also referred to as 2D Simulation, is a method that assesses risk by scoring the probability of occurrence and impact for identified risk events. Uncertainty and variability can be reproduced simultaneously, and their influence on the results can be assessed separately. This is done by separately sampling the distributions representing uncertainty and variability [105].
Reference [106] emphasizes the significance of clearly differentiating uncertainty from variability in risk analysis.

- Uncertainty is an assumption that is uncertain because of a lack of sufficient information about its true but unknown value, in which it is possible to eliminate the uncertainty by gathering more information and practice. Such information may be missing because no one has gathered it or because collecting it is too costly or challenging.
- Variability is an assumption that changes because it describes a population with different values. Variability is inherent to the system, and it is impossible to eliminate it even by gathering more information.

Theoretically, 2D Simulation comprises a Monte Carlo simulation tool that runs an outer loop to simulate the uncertainty values and then freezes the uncertainty values while running an inner loop (of the entire model) to simulate the variability [107]. This process repeats for some external simulations, providing a snapshot of how the forecast distribution varies because of uncertainty.

In risk analysis, one must widely consider the two sources of variation (uncertainty and variability) linked to the 2D simulation concept. [107]. Several risk studies treat sources of variation only as uncertainty, but it is necessary to recognize that uncertainty and variability are distinct sources of variation. Therefore, one should approach them separately for a reliable risk characterization [108]. 2D Simulation allows more accurate detection variation in a prediction because of a lack of knowledge and variation produced by natural variability in a measurement or population, making it better than traditional one-dimensional simulation; besides showing the actual probability of risk, it is also possible to characterize it [109].

3. SYSTEMATIC LITERATURE REVIEW

3.1 Research procedures

This research step was conducted through a systematic literature review, adopted as an empirical method (see Fig. 3.1). The guidelines and the systematic review protocol model proposed by Kitchenham and Charters [110] supported the methodology of this study, including several activities, which can be grouped into four main phases: SLR review, SLR planning, SLR conduct, and SLR reporting.

In Fig. 3.5, the first phase concerns the review details (green color). In the yellow part, the second phase focuses on reviewing planning and incorporating research protocols. The color blue represents the third phase of the study on review conduction. The fourth phase presents the review report, covering conclusions, limitations, and validity threats (designated in orange). The SLR was motivated by the closer integration of knowledge on economic energy that involves investment, risk, and decision-making aspects in renewable energy projects, such as green hydrogen. The gap between development processes, methodologies, analyses, evaluations, ratings, and traditional tools used to evaluate investment in renewable systems also contributes to the need for this SLR.

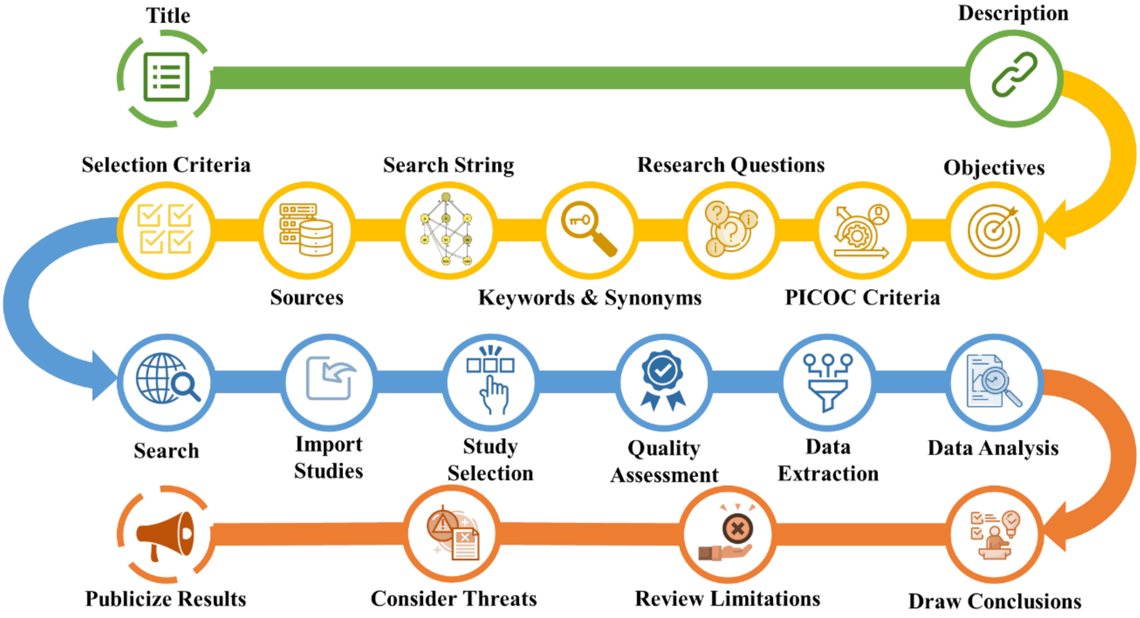

Fig. 3.1. Steps of the systematic literature review.

Source: elaborated from [110].

A search was conducted (in October 2022) to determine whether an SLR on financial indicators for analyzing green hydrogen investments had already been conducted. None of the retrieved studies were directly related to the objectives expressed in the research questions - only a critical analysis addressing the competitiveness indicators for energy projects in a general context [111]; however, the review did not have a systematic character and a study specifically on two embedded energy (energy payback time - EPBT, and energy return on energy invested - EROI) for photovoltaic solar systems [112]. There is a lack of systematic literature reviews on financial indicators to analyze investments in renewable energy, especially in green hydrogen projects.

3.2 Research questions

This systematic review aims to investigate the financial indicators used in the analysis of investments in green hydrogen for a better understanding of their status in financial engineering. Thus, it should answer the research questions described in Table 3.1.

TABLE 3.1. RESEARCH QUESTIONS AND MOTIVATIONS.

#	Research Question	Motivation
1	What financial indicators are used for investment analysis in green hydrogen projects?	This question aims to identify and analyze the financial indicators used to analyze investment in green hydrogen.
2	Are there any financial indicators associated with risk?	This question intends to detect the type of financial indicator used and how it is associated with the investment during the analysis.
3	What approach is used in investment analysis in green hydrogen projects?	This question aims to verify if the analysis has a stochastic or deterministic approach.

3.3 Search Approach

The search strategy included an automatic search using a validated string that relates the area of renewable energy (green hydrogen) to financial engineering. The review protocol (Step 2, Fig. 3.1) was developed following the PICOC criteria [110], [113], as shown in Fig. 3.6.

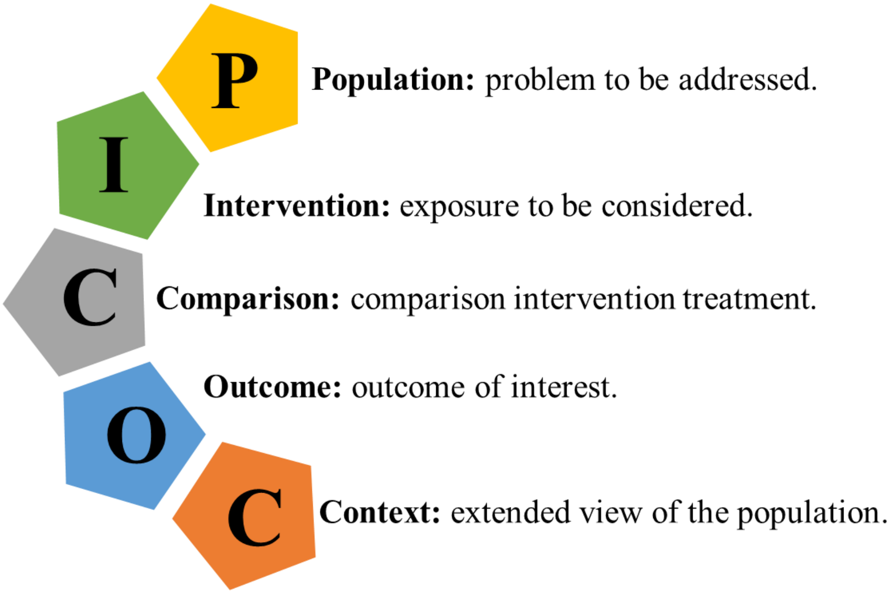

Fig. 3.2. PICOC criteria.
Source: elaborated from [110], [113].

- **Population:** Peer-reviewed publications on green hydrogen;
- **Intervention:** aimed to collect evidence regarding economic and financial studies related to investments in green hydrogen;
- **Comparison:** it does not apply;
- **Outcomes:** presentation of financial indicators;
- **Context:** particular settings or areas of the population in renewable energy sources.

Furthermore, the selected resources were Web of Science, IEEE Xplore, ScienceDirect, and Scopus, and the search method comprised a web search in digital databases. The search string was specified considering the main terms of the investigated phenomena (“green hydrogen,” “economic feasibility,” “techno-economic,” “net present value,” “levelized cost of hydrogen,” and “omega ratio”). Pilot searches were performed to refine the search string iteratively. Keywords whose inclusion did not return additional articles in the automatic searches were excluded, and after several iterations, the following search string was defined and used to search for keywords, titles, abstracts, and full text of publications:

(1) *("green hydrogen"* OR *"renewable hydrogen")* AND

(2) *("cost of hydrogen"* OR *"economic analysis"* OR *"economic assessment"* OR *"economic evaluation"* OR *"economic feasibility"* OR *"economic viability"* OR *"techno-economic")* AND

(3) *"internal rate of return"* OR *"modified internal rate of return"* OR *"levelized cost of hydrogen"* OR *"life-cycle cost analysis" OR "net present value"* OR *"payback"* OR *"return on investment"* OR *"total life-cycle cost"* OR *"weighted average cost of capital"* OR *"value at risk"* OR *"conditional value at risk"* OR *"omega ratio"* OR *"fisher's rate")*

Keywords related to green hydrogen are presented in the first group of terms, and the second concerns economic and financial studies. The third is the financial indicators. The Parsifal tool [114] (Perform Systematic Literature Reviews) was used to support the protocol definition and the conduction of the SLR because of the positive results in executing the SLRs [115], [116], [117].

3.4 Inclusion and exclusion criteria

Inclusion and exclusion criteria were specified to filter the articles for this study and are presented in Table 3.2.

TABLE 3.2. INCLUSION/EXCLUSION CRITERIA.

Criteria	**Subject**
Inclusion	Primary studies
	Studies dealing with green hydrogen
	Studies dealing with renewable hydrogen
Exclusion	Out of scope
	Gray literature
	Duplicated article
	Secondary and tertiary studies
	Investment analysis is not the primary goal of the work
	Publications whose text was not available (through search engines)

Only primary studies are of interest in this paper, primarily published between 2018-2022, which presents a contribution to using financial indicators to analyze investments in green hydrogen.

3.5 Procedure for studies selection

The study selection procedure was embraced in four main steps. Fig. 3.3 shows the input and output of each stage with two tables containing the exclusion criteria applied only to the studies in Stages 3 and 4.

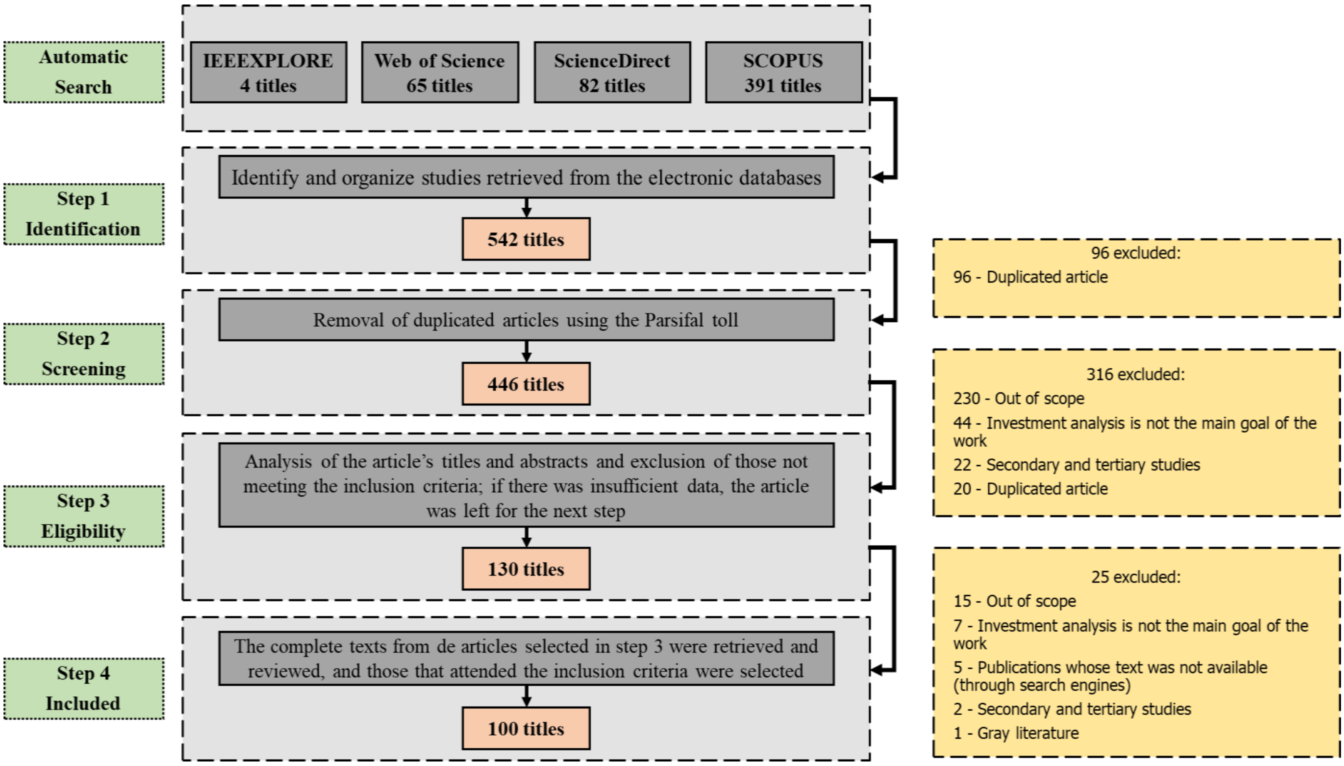

Fig. 3.3. Article selection flowchart.

In Step 1, studies were done using a search string from electronic databases. IEEE XPLORE returned only four titles, 65 in Web of Science, 82 in ScienceDirect, and Scopus 391 search results. The search results (542) were downloaded, typed, and organized using the Parsifal tool. Of the 542 search results, 446 were unique (step 2). After reading the articles' titles and abstracts, 316 were excluded based on the exclusion criteria. At the end of Stage 3, 130 articles remained in the selection process.

After reading and analyzing 130 articles (step 4), 100 relevant articles were obtained. In this step, the articles were also rejected according to the same exclusion criteria (-30 articles) considered in the previous step, as stated in Fig. 3.3 Several studies were excluded from this SLR, mainly addressing the production of hydrogen not categorized as green hydrogen. Thus, articles were selected that only aim to analyze investment in the production of green hydrogen.

3.6 Data extraction and synthesis

Digital forms were prepared to record any information needed to answer the research questions accurately. Data from each of the 90 primary studies included in this systematic review were extracted and are described in Table 3.3. The data extraction process was implemented mainly by the Parsifal tool. Terms describing the same phenomenon were normalized in the synthesis phase to use the more common term.

TABLE 3.3. DATA EXTRACTION FORM.

#	Article Data	Description	Relevant RQ

1	Article identifier	Exclusive ID for the study	Study overview
2	Authors		Study overview
3	Title		Study overview
4	Year		Study overview
5	Country		Study overview
6	Article source database	IEEE, Web of Science, ScienceDirect, Scopus	Study overview
7	Type of article	Journal, conference, symposium, workshop, book chapter	Study overview
7	Article publication source	Journal, Book, or Conference description	Study overview
9	Currency	AU$, CAD, NZD, R$, US$, £, ¥, €	Study overview
10	Financial indicators	Which financial indicators were used in the analysis?	RQ1
11	Financial indicators	Are there any financial indicators associated with risk?	RQ2
12	Approach design	Does the study have a deterministic or stochastic approach?	RQ3

3.7 Quality assessment

Assessing the quality of an SLR is critical for understanding quality differences and explaining differences in study results [110], [118]. Quality guidelines consider SLR quality to be related to the level to which the study minimizes bias and maximizes internal and external validity [110]. In this SLR, a quality assessment (QA) of the selected studies was performed using a scoring technique to assess credibility, integrity, and relevance. All articles were evaluated through a set containing ten quality criteria, presented in Table 3.4.

Each quality assessment question is judged against three answers: “Yes” (score = 1), “Partially” (score = 0.5), or “No” (score = 0). Consequently, the quality score for a study is calculated by summing the scores from the answers to questions related to its type of research, totaling a maximum of 10 points. The quality scores of the chosen studies are presented in Table 11.1 (see Appendix A).

TABLE 3.4. STUDY QUALITY EVALUATION CRITERIA.

#	**Question**	**Focus**
1	Does the paper have highlights and a graphical abstract?	Design view
2	Is there a clear statement of the study goals primarily focusing on analyzing green hydrogen investments?	Economic view
3	Does the paper present a financial indicator?	Economic view
4	Does the paper present a financial indicator associated with risk?	Economic view
5	Does the paper have a stochastic approach?	Technical view
6	Are the results clear and concise?	Design view

7	Is there a discussion about the results of the study?	Design view
8	Does the study perform sensitivity analysis?	Technical view
9	Do the authors describe the study's limitations and lay the foundations for further work?	Design view
10	Was the study cited? "Yes" for over five citations, "Partially" for up to 5 citations, and "No" for no citations.	Impact view

3.8 Results analysis

This section explains the study's results, where the answers found in the identified literature for each research question are discussed separately. The quality assessment increased the reliability of the conclusions obtained in this study, making it possible to verify the credibility and the coherent synthesis of the results.

3.8.1 Quality assessment results

The quality assessment made it possible to enhance the reliability of this review's conclusions and verify the credibility and consistent synthesis of the results. The quality evaluation results of the studies included in Table 11.1 (see Appendix A) are presented according to the assessment questions described in the Table. These ten criteria provided a weighting of reliability that a particular selected study could make a valuable contribution to this review. The general quality of the selected articles is reasonable, with an average quality of 60.80% on a scale of 0 to 10.

3.8.2 General view of the articles

The selected articles were published between 2018 and 2022. In Fig. 3.4, the number of studies per year of publication is presented. An increasing number of publications in this review's context can be noted, especially for 2022 (with 51 articles).

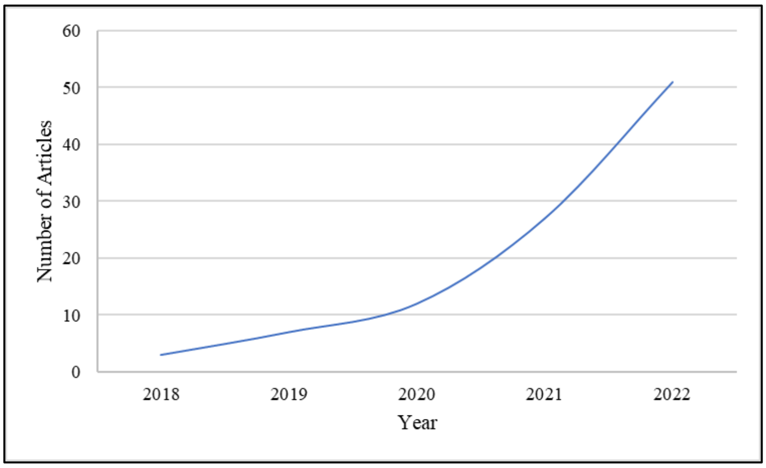

Fig. 3.4. Temporal view of the articles.

When analyzing the temporal view of the articles, it is possible to infer that the number of papers on green hydrogen with a bias towards techno-economic and investment analyses has grown in the last five years. This result corroborates this thesis' proposal, showing the theme's lightness and importance in the hydrogen economy as an emerging area of study [119]. Then, the distribution of selected articles was analyzed according to the authors' countries of affiliation, shown in Fig. 3.5.

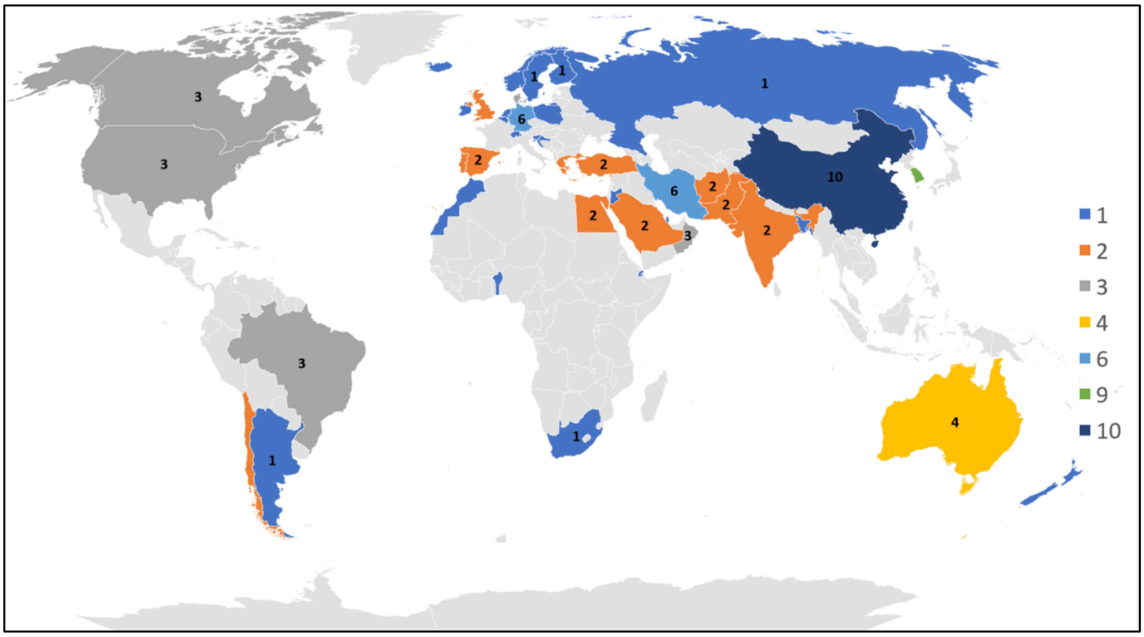

Fig. 3.5. Articles by country of affiliation.

This result validates the proposal made by this thesis, showcasing the significance of the theme and its relevance within the context of the hydrogen economy. The articles belong to several countries, with Australia, Germany, Iran, South Korea, and China being the most common. Regarding analysis, the Asian continent is taking the lead, with China having the most significant number of articles (10) in this domain, closely followed by South Korea (9 articles) in the second position. Iran and Germany appear tied with six articles, and Australia (4). China is firmly committed to reducing carbon emissions, with significant investment policies in green hydrogen, profoundly impacting the production and storage of green hydrogen in the coming years [119]. The results of each Research Question (RQ) are presented and discussed in the following sections.

3.8.3 RQ1: What financial indicators are used for investment analysis in green hydrogen projects?

This question intends to detect which financial indicators are used to analyze investment in green hydrogen production. In each research question, a detailed discussion of the results is provided. Table 3.5 lists the financial indicators of selected articles that investigated the analysis of investment in green hydrogen, whose results are discussed below.

TABLE 3.5. FINANCIAL INDICATORS FOR INVESTMENT ANALYSIS.

Financial indicator	**Count**	**%**
Benefit-Cost Ratio (BCR)	1	1.0%
Economic Value Added (EVA®)	1	1.0%
Return on investment (ROI)	1	1.0%
Total Cost of Ownership (TCO)	1	1.0%
Total Life-Cycle Cost (TLCC)	2	2.0%
Life-Cycle Cost Analysis (LCCA)	11	11.0%
Internal Rate of Return (IRR)	13	13.0%
Weighted Average Capital Cost (WACC)	13	13.0%
PAYBACK	28	28.0%
Net Present Value (NPV)	29	29.0%
Levelized Cost of Hydrogen (LCOH)	82	82.0%

The results show a level of preference in the literature for choosing a particular financial indicator. 8 out of 10 articles use LCOH for investment analysis in green hydrogen, in which LCOH appeared almost three times more than the second most used index, NPV, which was present in 29 of the 100 articles in this review. It was also observed that 40 articles only use LCOH as a metric for their analyses, showing that the use of LCOH has become a widespread practice as it is a convenient indicator of the competitiveness of different hydrogen generation technologies, integrating some of the main cost variables of these technologies [120]. It is essential to note that LCOH measures the cost, not the green hydrogen value. Therefore, it is necessary to understand that LCOH cannot be the only metric used as a single criterion for decision-making.

NPV was the second most used indicator, with 29 articles. The analysis also shows that in 10 studies, NPV was used with LCOH, combining the cost of producing green hydrogen with the analysis of return and real gain on investment, considering the capital appreciation. After NPV, it appears with payback as the third most used metric. For decades, payback has been used as a metric for analyzing investments in the energy sector because increasingly efficient energy options have supported human progress, and such efficiency can be measured using payback [121]. Another highlight is that the use of payback and its increase may show that hydrogen has become an option for general acceptance to mitigate climate change, as history shows that economic and social progress depends on options with high payback values [121].

WACC, IRR, and LCCA were metrics that appeared between 10-15% in the analyzed articles. WACC is a robust method that is very relevant to NPV and LCOH prediction calculations. Using the WACC contributes to increasing the comparability of a study [122], and as it is an indicator influenced by the exposure to the systemic risk inherent to the market and the perceptions of this risk by investors [66], it was expected that its presence would be more frequent in the analyzes that used the NPV and LCOH. However, it was observed that WACC was present in only 11 studies involving LCOH and four studies involving NPV, demonstrating that, although appropriate in principle for decision-making, WACC is often neglected in global investment assessments.

NPV and IRR can classify mutually exclusive projects differently because of different scales, costs, and lifetimes, leading to confusion in selection [123]. For example, depending on the initial investment costs, a project may have a low IRR in that project being slow, and the project may also add a large amount of overall value to the organization. In another example, it found that an NPV of an investment with a longer duration but a lower IRR may be more significant than an NPV of a related investment (in terms of total net cash flows) with a shorter duration and a higher IRR [124]. One explanation for this is that both projects can implicitly assume the reinvestment of returns at their rates (i.e.,% for NPV and IRR% for IRR), in which the project with the highest positive NPV may not be the project with higher IRR, as the reinvestment rates are different [123]. Therefore, this will lead to a different classification, and then it is recommended to use IRR only when considering acceptance/rejection analysis for single projects with conventional cash flows [125], [126]. Thus, the authors prefer not to consider the IRR in their studies because the IRR has limitations and disadvantages, such as the assumption that investments (negative cash flows) are financed at a rate equal to the IRR. One way out of the limitations and complexity of calculating the IRR would be to use the Modified Internal Rate of Return (MIRR); however, this measure was not observed in any of the investigated articles and, therefore, was not discussed in the review.

The authors of 11 analyzed papers used an investment analysis approach by summing the costs over the life cycle of green hydrogen through the LCCA. When analyzing the works that used the LCCA, it was possible to perceive that the investment analysis was strictly related to optimizing the green hydrogen production system using the *HOMER Pro Software*®. Additionally, it was identified that the software, when performing the system optimization process, also had a solution that allowed calculating the life-cycle cost of each system component and the system [127].

Life cycle cost analysis is an approach that evaluates the total cost of an asset over its life cycle, from initial capital costs, maintenance costs, and operating costs to the residual value donated at the end of its useful life [128]. Usually, LCCA has been loosely defined as a methodology that allows cost comparisons over a specific period, considering relevant integral economic factors; in the past, it was employed to optimize product implementation and the lifetime cost of ownership [129].

Four less-used indicators had a single appearance in the analyzed articles; among the 4, the TCO was the only indicator used in the investment analysis without another. The others were used with other metrics. TCO is an indicator widely applied in the information technology sector and has a certain complexity for its calculation, as it is an arduous, tedious analysis and quickly takes a year [130]. The above discussion denotes a cause of TCO's low and unique use.

TCO is understood as the average point cost of a technology solution over a portion of its lifetime: design, build, test, implementation, operational support, and/or decommissioning [131]. Like TCO, there is ROI in which both indicators allow organizations to identify the time needed to cover their costs based on their choice of solution and implementation requirements [132]. ROI is a popular accounting metric for comparing business investments, which comprises the present value of the net benefits accrued over a period divided by the investment's initial costs [133]. It is worth mentioning that TCO assessment goes beyond ROI and encompasses the value of deploying and maintaining a platform/framework. This includes considering the time required to implement and operate a solution, as the perception of value varies depending on the organization's standpoint [132].

EVA® was another indicator present. Stern Stewart and Company (presently Stern Value Management (SVM)) developed the metric to meet this need, which was widely adopted in the 1990s. Its measurement has been used to guide investment decisions and is frequently used in determining management compensation [134]. Cost/benefit analysis was also present in one study, aiming to determine whether the additional upfront costs of a more expensive green hydrogen system are merited considering long-term cost factors [135]. Last, with a mere two instances, was the TLCC. After examining the specialized literature, the LCCA and the TLCC exhibit identical theoretical principles and calculation methods.

3.8.4 RQ2: Are there any financial indicators associated with risk?

The second research question aimed to investigate whether the indicators have any connection with the project's financial risk, but first, for a better understanding, how the indicators were applied will be exposed. Fig. 3.6 presents the indicators observed in the analyzed articles.

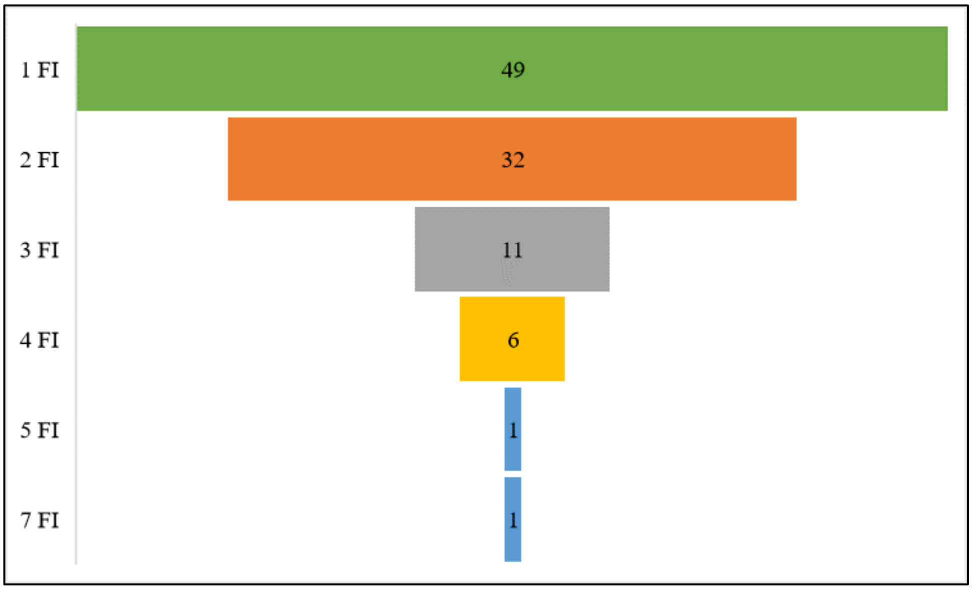

Fig. 3.6. Number of financial indicators per study.

Fig 3.6 shows the number of indicators per article, represented by the "y" axis of the chart, where FI means financial indicator. In the figure, it is also possible to observe that most works used only one metric to analyze the investment (49 papers), specifically the LCOH. Thirty-two articles used the combination of 2 indicators; 11 papers used three metrics; four indicators were used in 6 analyses, and only two studies applied 5 and 7 indicators, respectively. Subsequently, Fig 3.7 is presented to complement the results of Fig 3.6, presenting a broader view of how the indicators were used in the studies, either individually or in combination with other indicators. In addition, the appearance frequency with which the indicators were used in the articles is also presented.

In every paper, the LCOH was used alongside at least one other indicator, except for TCO, which was employed individually in only one study. Among all the indicators, the NPV stands out with the most significant number of combinations, totaling 13 different uses. Furthermore, in 11 distinct approaches, the LCOH was employed alongside the other metrics, with the PAYBACK ranking third and achieving nine combinations. A comprehensive evaluation, whether through a keyword search for "risk" or a thorough reading of the articles, shows that the analysis of investments in green hydrogen projects lacks consideration of financial risk.

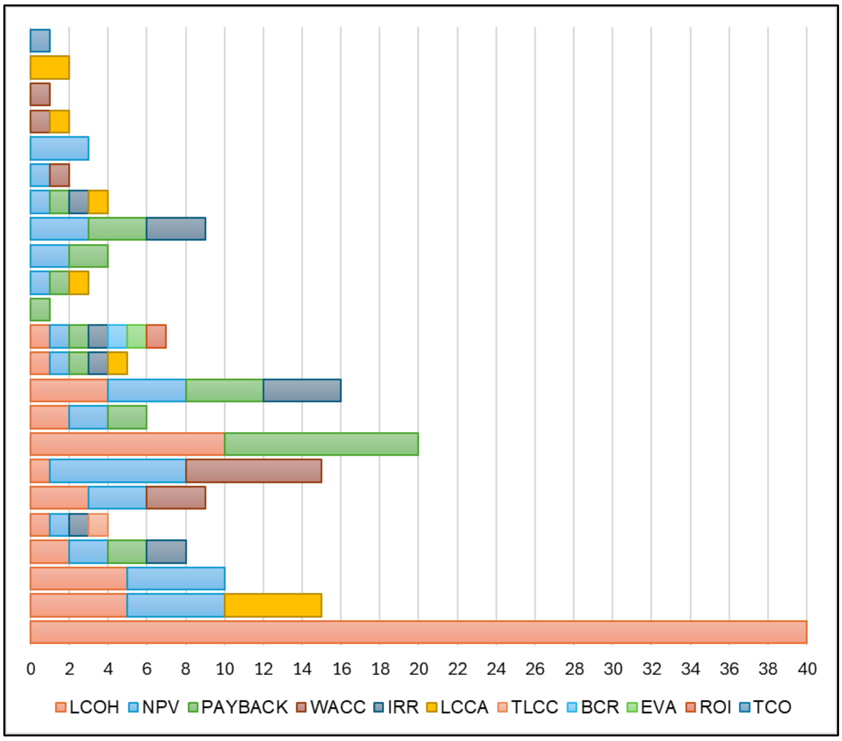

Fig. 3.7. Arrangement and frequency of financial indicators.

The selected studies cited these indicators as metrics that the authors used to analyze investments unrelated to financial risk. The articles did not expressly mention that such indicators were related to project risk. When the term “risk” was approached, there were sporadic mentions superficially, without further details in which there was no connection to its measurement or any other pertinent analysis. This SLR aims to strengthen the innovation of the thesis and clarify the gap between analyzing investments in green hydrogen and considering parameters that investigate the financial risks associated with the uncertainties of projects. By providing a thorough analysis, it aims to facilitate better investment management and support decision-making processes.

3.8.5 RQ3: What approach is used in investment analysis in green hydrogen projects?

This question maps the approaches used by the authors to conduct investment analyses. The approaches were classified as deterministic and stochastic [136]. Fig. 3.8 presents the approaches used in the studies classified into deterministic and stochastic analysis.

The analysis of Fig. 3.8 shows that 83% of studies use a deterministic approach against only 17% for stochastic analysis. This result shows the need to develop probabilistic frameworks and models capable of integrating the specifications of green hydrogen generation technologies with knowledge of economic and financial engineering to obtain more accurate and reliable results considering the effect of uncertainties and conditions of risk according to random fluctuations in the variables. In addition, it was also possible to observe that 82% of the studies with a stochastic approach used the LCOH as the leading indicator for economic analysis.

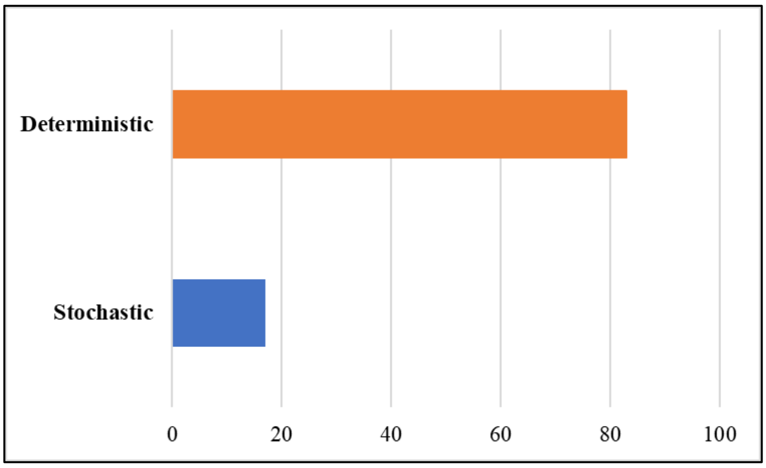

Fig. 3.8. Approach to investment analysis.

When analyzing the studies with a stochastic approach, it was observed that the articles have a higher quality than those that use only the deterministic approach. The average quality was 7.08, with a standard deviation of 0.79 and a median of 7.5 on a scale from 0 to 10. This is a strong sign that the stochastic approach has greater robustness since most of the time, from stochastic simulations, it is also possible to perform sensitivity analyses on the variables of uncertainties, providing the management of the risk of investment in green hydrogen projects and more reliability to the results.

Combining the stochastic approach with risk indicators can provide a more comprehensive understanding of the risks linked to green hydrogen projects. This approach allows for estimating results and their corresponding probabilities instead of relying solely on point values (as in the deterministic approach), which often deviate from reality.

3.9 Review limitations

The main limitations of this SLR are the omission of articles in the search process and bias in data extraction. The search process started with an automatic search strategy using primary electronic databases in hydrogen, financial engineering, and renewable energy. Considering the restrictions imposed by search engines, it was noted in the final assessment of this review that the automatic search omitted essential works in the field. Additionally, it was found that the utilization of certain terms could cause the inclusion of more studies in the area, further expanding the comprehensiveness of the search. In order to mitigate such problems, a manual search was conducted to improve the quality of the research results and to non-systematically analyze the studies' content concerning this thesis's innovation. After the analysis, it was observed that this research's character of innovation, quality, and originality was not compromised. As improvements, during the research execution of this thesis, such terms and, consequently, the articles from the search can be inserted in the SLR to make the systematic analysis even more complete.

Right from the start, the primary goal was to ensure utmost integrity in selecting articles. Furthermore, the review is subject to a limitation whereby relevant articles may be overlooked because of the absence of consensus in the fields of green hydrogen and financial analysis regarding terminology, as well as the possibility of pertinent articles existing that do not explicitly reference the specified terms. This shows that the selected keywords may not have covered all the articles published in the specific field of interest, such as the analysis of investments in green hydrogen. It is of utmost importance to underscore that the keywords about green hydrogen are not universally standardized and may differ across writings.

Regarding the bias of data extraction, specific difficulties were faced in extracting relevant information from the articles. A few articles do not present objective details about various issues to be addressed in the research questions. For example, some articles do not explicitly mention investment analysis as the main aim of the study, and the sign of financial indicators with the proper equations was not done systematically; some articles presented the indicators in the "case study" section, others in "methodology" and others even in the "results." On some occasions, it was necessary to interpret the subjective information provided by the articles.

A common issue encountered in studies is the lack of information about the methods used for evaluation. Some primary articles have poorly described data collection and analysis, which can affect the accuracy of data extraction and quality assessment. This limitation can lead to misunderstandings about how data was extracted from primary studies and threaten the validity of systematic literature reviews. The following section will address how to mitigate these threats.

3.10 Threats to validity

It was chosen to use the threat categorization proposed by Wohlin et al. [137], making an adaption that includes five categories, as shown in Fig. 3.9.

Construct validity is concerned with generalizing the result to the theory behind the research and establishing correct measures for the concepts being investigated [137]. In order to reduce potential threats, it was used various synonyms for main concepts in this review, including “economic analysis,” “economic assessment,” “economic evaluation,” “economic feasibility,” “economic viability,” and “techno-economic.” Then, in the synthesis phase, the terms that describe the same phenomenon were normalized to use the most common term [138]. The variations to deal with potential threats to the construct’s validity were also documented.

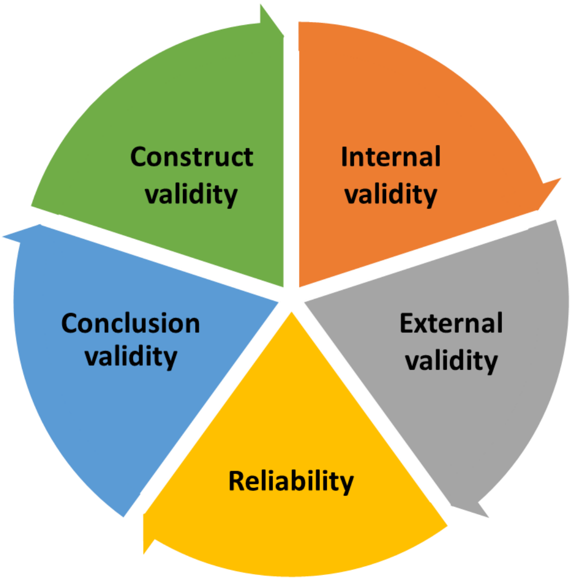

Fig. 3.9. Threats categorization.
Source: derived from [137].

Internal validity is related to possible erroneous conclusions about causal relationships between treatment and outcome, which may lead to other conditions [137]. In order to reduce potential threats to the internal validity of the research, emphasis is placed on the selection of primary studies and the evaluation of individual bias. The main source of data comprised journal papers, which was thoroughly reviewed multiple times to include as many primary studies as possible and to enhance the reliability of the conclusions. The personal bias in the study's understanding iteratively led to the selection process, resulting in a mitigating approach to addressing the threat.

External validity concerns the establishment of the domain to which the analysis results can be generalized and is related to the degree to which the primary studies represent the subject of the review [139], [140]. This systematic literature review focused on financial indicators for green hydrogen investment analysis for the last five years (2018-2022). As time passes, technologies for generating green hydrogen mature, leading to an increase in the economic viability of projects. Some studies may become obsolete in the future. However, as this review deals only with financial indicators for investment analysis, the results from this thesis can be generalized to broader periods or selections from broader primary studies, e.g., books and technical reports. The results were obtained through a qualitative analysis, excluding articles from the gray literature. Quantitative analysis and inferences can still be considered, allowing for analytical and statistical generalizations.

Reliability is related to the demonstration that the operations of this study can be reproduced, obtaining the same results. It is hoped that replications of this research will provide results similar to this analysis.

However, the characteristics of the research questions, research sequences, and primary studies may differ from this study, although the underlying trends should remain unchanged.

In conclusion validity, not all existing relevant primary studies can be identified [110]. This threat was mitigated by thoroughly designing and validating the research protocol, minimizing the risk of exclusion of relevant studies. As reported, sufficient synonyms for the constructs in this search were used to improve the high coverage of potentially significant studies of the automatic search. In addition, no additional manual searches were performed since the leading journals on green hydrogen and renewable energies were indexed by the search engines adopted in our protocol. As mentioned earlier, through information, this is the first SLR focusing specifically on financial indicators for analyzing green hydrogen investments related to its production.

3.11 Related works

Recently, researchers have conducted reviews with the various objectives of gathering and evaluating the evidence in hydrogen and renewable energies. Four review studies were identified: Green-hydrogen research [119], Societal acceptance and stakeholders' perception of hydrogen technologies [141], Competitiveness indicators for energy projects [111] and Energy payback time and Energy return on energy invested in PV systems [112]. Table 2.6 summarizes the contrast.

TABLE 3.6. COMPARISON OF RELATED REVIEWS.

Review design	**Review data**	**Authors**
Bibliometrics analysis	642 articles from 2016 to 2021	[119]
Systematic literature review	43 articles between January 2008 and October 2020	[141]
Critical review	Unmentioned	[111]
Systematic review and meta-analysis	34 articles from 2005 to 2008	[112]

Raman et al. [119] aimed to examine the evolution of green hydrogen research topics since the United Nations Sustainable Development Goals were adopted in 2015, using couplings, keyword co-occurrence, and key-phrase analysis based on Scopus data. The authors studied bibliometric indicators and the temporal evolution of publications and citations, open access patterns, the consequence of author collaboration, influential publications, and highest contributing countries, as well as considering new indicators such as publication views, key phrases, topics with field-weighted citation impact and highlights and metrics to understand the direction of research better. The review results align for four principal thematic distributions of green hydrogen research established on keyword co-occurrence groups: hydrogen storage, hydrogen production, electrolysis, and hydrogen economics. Four networks of research groups were also identified that provide new insights into contributions to green hydrogen research: hydrogen energy and cleaner production, applied energy, fuel cells, and materials chemistry. Finally, the study concludes that most green hydrogen research aligns with Clean and Affordable Energy and Climate Action.

Emodi et al. [141] presented the results of a systematic review that analyzed the literature on factors that influence societal acceptance and stakeholder perceptions of hydrogen-related technologies. The authors found that the most influential factors comprise prior perceived cost/risks, knowledge, environmental knowledge, personal and distributive benefits, higher education and income, availability of infrastructure, and proximity to hydrogen facilities.

Colla, Ioannou, and Falcone [111] reviewed and critically investigated a set of multidisciplinary Key Performance Indicators (KPIs), allowing for a holistic comparison between different energy projects. The indicators were classified into physical, economic, environmental, and social and further analyzed to assess their limitations, determine interconnections, and identify the need for additional indicators to capture risks and opportunities within a mixed energy market. The authors intended to create a document that can be the basis for developing an integrated framework, allowing for a fairer assessment of competing energy projects by relevant stakeholders.

Regarding using a stochastic approach for analyzing investments in green hydrogen considering uncertainties and indicators associated with risk, as far as the author knows, there are still no works that address this nuance as of this thesis. Using the Web of Sciences database (by Clarivate Analytics), terms such as economic analysis, Levelized cost of Hydrogen, Hydrogen, stochastic, uncertainty, and risk were explored until the writing of this text for references. This investigation documented the absence of studies addressing risk measures, especially Value at Risk (VaR), Conditional Value at Risk (CVaR), and Omega ratio, for the technical and economic evaluation of green hydrogen projects. Table 3.7 summarizes the search terms together with the number of papers identified.

TABLE 3.7. PAPER SEARCH TERMS.

Search	SLR Search Terms	Structure Location	Amount
1	("Techno-economic" OR "Economic evaluation" OR "Economic feasibility" OR "Economic viability" OR "Economic analysis" OR "Economic assessment" OR "Levelized cost of hydrogen")	All fields	81085
2	AND ("Hydrogen")	All fields	3216
3	AND (“Stochastic")	All fields	34
4	AND ("Uncertainties" OR "Risk" OR "Uncertainty")	All fields	18
5	AND (“Omega” OR “Omega ratio” OR “Value at Risk” OR “Conditional Value at Risk”)	All fields	0

Even in large areas of energy systems, few investment analyses consider all the aspects discussed in this thesis. Six papers were identified with aspects related to this research, as presented in Table 3.8.

TABLE 3.8. COMPARISON OF RELATED WORKS.

Financial Indicators	**Approach**	**Uncertainties**	**Source**
Internal Rate of Return (IRR) Conditional Value at Risk (CVaR)	Stochastic	Wind speed	[142]
Levelized Cost of Electricity (LCOE) Constant relative risk aversion function	Stochastic	Carbon pricing; Variability for the renewable generation	[143]
Levelized Cost of Electricity (LCOE) Standard Deviation Conditional Value at Risk Deviation (CVaRD)	Stochastic	Nuclear power plant construction times	[144]
Net Present Value (VPL) Conditional Value-at-Risk (CVaR)	Stochastic	Future hydrothermal dispatch	[145]
Levelized Cost of Electricity (LCOE) Omega ratio (Ω)	Stochastic	Wind speed	[87]
Levelized Cost of Electricity (LCOE) Conditional Value-at-Risk (CVaR)	Stochastic	Solar irradiation	[67]

As of this study, there is no knowledge of a systematic review of financial indicators for the analysis of investment in green hydrogen. This SLR fills the gap by summarizing the indicators used in the analyzed articles. Like the SLR, this thesis fills the gap in the green hydrogen investment analysis field by proposing a framework encompassing the uncertainties and indicators associated with financial risk through stochastic simulation, proving a unique and original work.

3.12 Findings outline

The review's findings show a growing volume of studies related to green hydrogen and the analysis of investments in this potential source of decarbonization of systems. In 2022, the number of articles almost doubled compared to the equal period in the previous year; compared with 2018, it is possible to observe a growth of 1,600% relative to 2022. China and South Korea were most interested in analyzing investments in green hydrogen generation projects, with a share of 10% and 9% of the studies, respectively. Asia is at the forefront regarding producing peer-reviewed literature on the topic addressed in this SLR, with approximately 48% of the study concentrated on the continent.

This SLR shed light on the financial indicators used in the analysis of investments in hydrogen, pointing to LCOH as the index of significant preference in the literature, present in 82% of the articles. Eleven indicators were used for the investment analysis; however, it was observed that the LCCA and TLCC have the same theoretical approach and are considered the same indicator, as they have the same input data and lead to the same results. Thus, ten indicators were used by the articles investigated in this review.

The financial indicators used in the studies investigated in this SLR are not related to project risk, showing the gap in the literature for assessing financial risk in green hydrogen investments and confirming a particular deficiency in financial risk management by the studies. Risk is a preponderant factor for good investment analysis, and its weighting, especially for new technologies, such as green hydrogen generation technologies with a capital-intensive character, must be considered to make investments more reliable and manageable.

In conclusion, it is crucial to bring attention to yet another void in the existing body of literature regarding the prevailing use of deterministic models in investment analysis. The findings show that a minority of the literature has applied stochastic methodologies in their evaluations, specifically representing 18% of the studies. Notably, 82% of these studies opted for stochastic simulations to estimate the input parameters for LCOH estimation. Knowing that the production of green hydrogen is associated with several uncertainties and that these can impact investment analysis, it is necessary to understand that such analyses need probabilistic methods so that decision-making in projects that consider the randomness and heterogeneity of the variables increases the credibility of the analysis.

4. THE STOCHASTIC TECHNO-ECONOMIC FRAMEWORK (STEF-H2V)

This chapter presents the STEF-H2V structure, specifically the methodology employed to investigate the complexities (variabilities and uncertainties) associated with green hydrogen production. This research focuses on hydrogen production using polymer electrolyte membrane (PEM) water electrolysis technology through land-based wind and solar photovoltaic resources on either a distributed or utility scale. The approach proposed in this thesis seeks to offer decision-makers in investment, policymaking, and government a robust and holistic framework to assess and techno-economically compare investment situations in green hydrogen projects.

The research intends to investigate the potential of investments in green hydrogen using financial indicators (WACC, CAPM, and LCOH) and risk measures such as VaR, CVaR, and Omega ratio as financial indicators associated with risk, stochastically simulated. Accordingly, a comparative evaluation can be conducted to determine the extent to which the stochastic approach yields more valuable information compared to deterministic analysis. By considering uncertainties and financial indicators associated with risk in the analyses, decision-makers can access reliable data. Therefore, identifying risks in green hydrogen projects becomes essential (based on a systematic approach) for new investments to be trustworthy since green hydrogen plants have a capital-intensive character. The framework's methodological structure comprises four primary steps, as shown in the diagram in Fig. 4.1.

The initial step involved conducting a Systematic Literature Review (SLR) to examine and refine the financial indicators used in TEA for green hydrogen. This process also evaluated the methodologies employed and their integration of uncertainty and variability to address investment financial risk management. The subsequent step involved two doctoral internships conducted abroad, specifically designed to deepen comprehension of the methodologies employed in evaluating investments in green hydrogen. A significant focus was placed on investigating the models and tools applied for this type of evaluation. During the third step, the framework was structured and refined to maximize the assessment's robustness, effectiveness, and resemblance to real-world scenarios. Moreover, this step also outlined the assumptions that would be used for conducting the simulations, besides the risk measures employed for managing financial risk. Ultimately, the simulations were executed and applied in case studies to assess the framework's performance, resulting in the development of an approach that integrates financial risk management into TEA for green hydrogen investments.

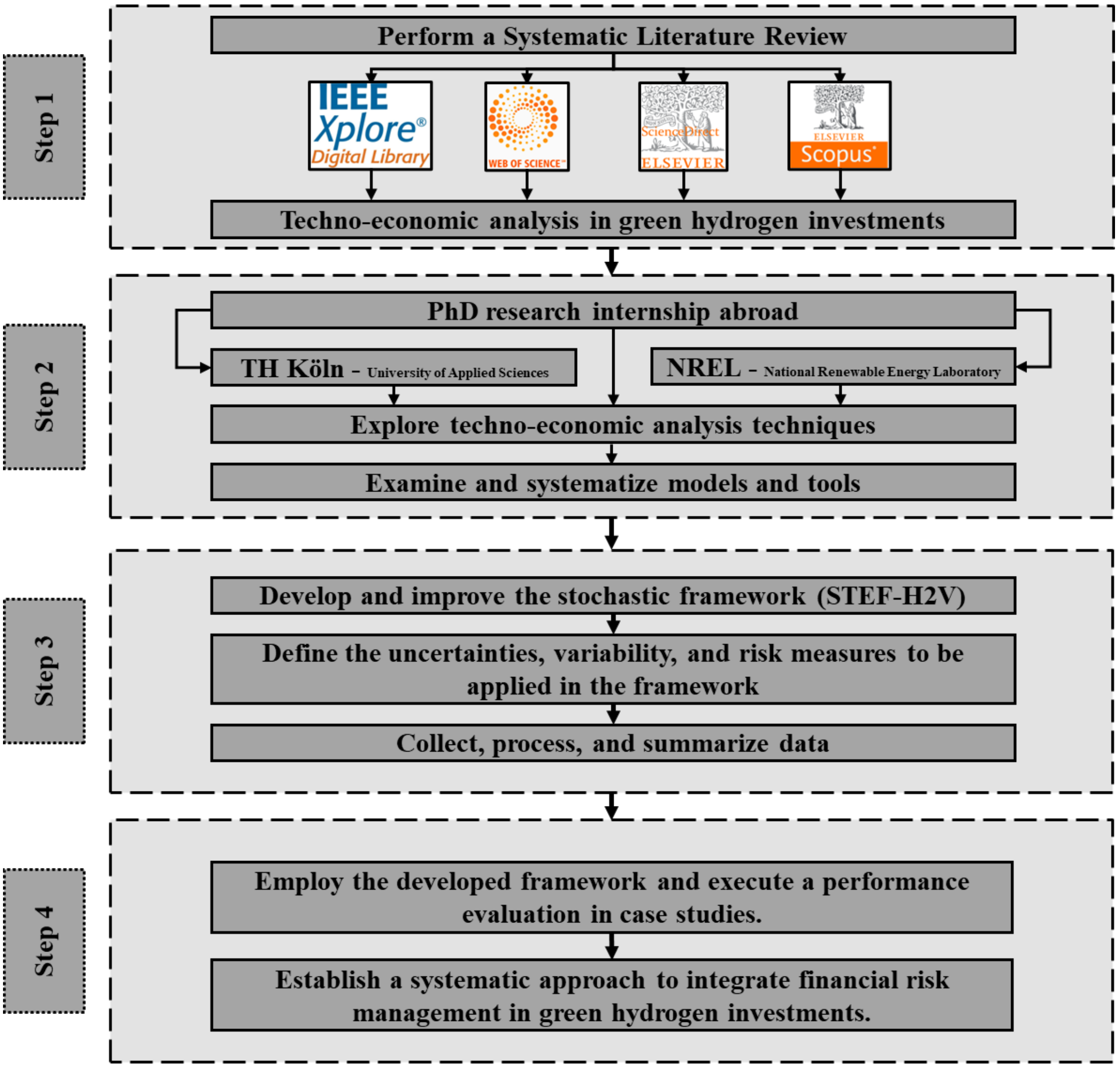

Fig. 4.1. Framework's methodological structure.

The framework primarily emphasizes hydrogen production through water electrolysis using renewable resources. The initial case study (chapter 5) was implemented on a distributed scale in Itajubá, Brazil, and Cologne, Germany. It is noteworthy that the German Agency International Cooperation (GIZ - Gesellschaft für Internationale Zusammenarbeit) chose the Federal University of Itajubá to allocate 5 million Euros for the construction of the Center for Production and Research in Green Hydrogen [34]. In the second case study (chapter 6), the STEF-H2V was used at a utility-scale in eight states across Brazil, where it underwent enhancements to achieve a more robust analysis, placing significant emphasis on integrating financial risk management with TEA. The framework's third implementation aimed to differentiate the sources of variation in another case study, in which variability and uncertainty were separately and independently simulated using two-dimensional simulation (chapter 7).

The framework evaluates green hydrogen investments by stochastically simulating the input assumption that impacts LCOH in grid-connected systems equipped with Proton Exchange Membrane electrolyzers. PEM electrolysis is an up-and-coming technology for producing green hydrogen because of its high flexibility, efficiency, and compact design [95], [146], [147]. The framework's adaptability enables the assessment of other electrolyzer technologies, power generation, and different scales. The framework incorporates a stochastic approach through Monte Carlo simulation, considering uncertainty and variability (technical and economic) and financial indicators associated with the risk of estimating the cost of producing green hydrogen. The framework’s layout (see Fig 4.2) comprises two tabs in Excel. The first tab concerns information ranging from system data to cost estimation (section one to section seven), and the second concerns financial risk management (section eight). By utilizing the second tab, it is possible to incorporate the risk measures into TEA by leveraging the outputs derived after the stochastic simulation.

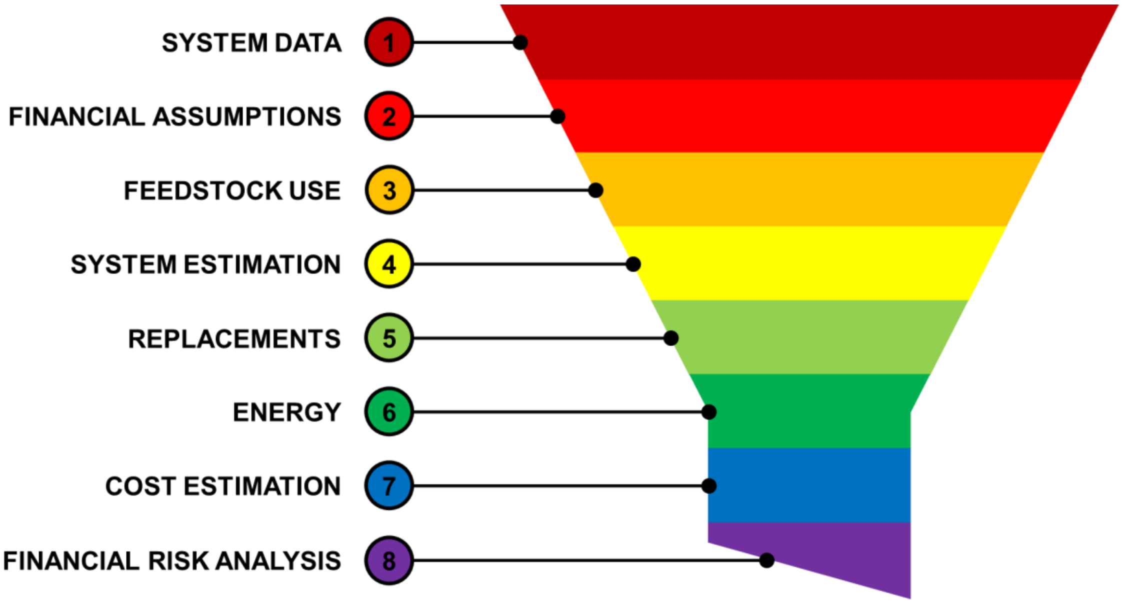

Fig. 4.2. Framework's layout.

The system estimation section contains key data points and parameters related to the overall system being analyzed within the framework, including system specifications, operational parameters, and other relevant details related to renewable systems (wind and solar PV) and the electrolyzer system. Section 2 outlines the financial assumptions underpinning the framework's stochastic simulation. This includes assumptions about interest rates, inflation rates, depreciation methods, and other financial factors influencing the analysis. The financing section is divided into subsections, with general assumptions and capital costs, where the interest rate is estimated using WACC and CAPM, depreciation, financing and amortization, and incentives are estimated.

In section 3, feedstock use focuses on the input materials and resources (feedstock) used in the system or process being analyzed, detailing the inputs of feedstock, quantities required, sourcing methods, and any related considerations. The system estimation section estimates various aspects of the system's operation, encompassing estimation related to utilization, system capacity, system lifetime, and operation time.

Section 5 deals with replacing equipment, components, or other system assets, including forecasting replacement cycles, costs associated with replacements, and their impact on system performance and durability.

Subsequently, section 6 details the energy production aspects of the system, including projections and actual data related to electricity output about the renewable systems that can be used in the evaluation, as well as the hydrogen generation. This section also presents the assumptions related to the variability of the system, especially the solar radiation and wind speed. After section 6, it is possible to estimate the costs associated with the system (section 7). This section involves the capital expenses, operating expenses, maintenance costs, replacement costs, and any other relevant expenditures, including detailed cost breakdowns and calculations.

The final section, section 8, is tasked with evaluating the financial risks related to the project. This comprises conducting a financial risk evaluation using risk measures, exploring aspects related to the sensitivity analyses of the assumptions, scenario simulation, and other risk assessment techniques to evaluate the potential impact of various factors on financial outcomes. The outputs of the stochastic simulation, especially the levelized cost of hydrogen (LCOH), serve as a subsidy to manage the financial risk associated with green hydrogen investments.

LCOH is frequently used to categorize several hydrogen technologies and their competitiveness in different locations [30–35] and evaluate the regional policy impacts of enabling renewable hydrogen generation [77], [148], [149]. Nevertheless, with hydrogen from wind and PV sources, the LCOH calculation is complex because it involves intermittent sources, is commonly dimensioned without Battery Energy Storage Systems (BESS), and is influenced by geographical location. After all, the behavior of the climatic variable is different at every location. Therefore, this circumstance imposes uncertainty in hydrogen generation systems, which makes it relevant to evaluate the competitiveness from the financial risk viewpoint [150], [151], [152], [153].

The assessment of LCOH for green hydrogen by water electrolysis has received consideration in the literature from different approaches [80]. Most current research that estimates a deterministic LCOH addresses systems optimization models that include LCOH optimization as a purpose [151], [154], [155], [156], [157]. The LCOH calculated deterministically is also investigated in studies that evaluate the competitiveness and costs of other technologies and routes for hydrogen production, such as Steam Methane Reforming (SMR), nuclear hydrogen production, and hydrogen by biomass gasification [158], [159], [160], [161], [162].

Studies investigating LCOH from the perspective of uncertainty and risk are still limited, although some works investigate this point of view for calculating the Net Present Value (NPV) [74], [163], [164], [165],

[166], [167], [168]. A merged technique that uses computerized mathematics, capable of accounting for uncertainties in the estimation of LCOH, is the Monte Carlo Simulation (MCS), executed from a set of input variables randomly defined through predefined probability distributions [92], [93].

The uncertainty in the LCOH estimate has been investigated, focusing on competitiveness and technical-economic analysis between sources for hydrogen production [169], [170], [171], [172], [173]. Coppittters et al. quantified the uncertainties in hydrogen production through an optimization algorithm for several locations with the LCOH as an aim [174]. Addressing the role of uncertainties in the transition to hydrogen, Yates et al. explored input assumptions to identify key cost drivers, targets, and suitable locations for competitive stand-alone dedicated PV-powered hydrogen electrolysis, considering historical weather data and optimizing its size compared to the electrolyzer [171]. Komorowska et al. designed a framework to evaluate the location-based variability of LCOH and investigate the uncertainty in the long-term planning of hydrogen production installations [173]. Fazeli et al. examined the uncertainties in techno-economic factors linking techno-economic and uncertainty analysis with quantitative hydrogen supply-demand modeling [175]. Huang et al. established a techno-economic model to forecast the economics of integrated PV–hydrogen technology at central time points in the future based on this technology's characteristics, variability, and uncertainties [176]. Gerard et al. presented an economic risk analysis of green hydrogen generation from geothermal and solar energy resources through a MCS approach, applying a first version of a digital twin to design hydrogen facilities [177]. However, they did not apply risk measures to evaluate higher-risk scenarios for investors.

The distinctiveness of each analysis is enriched by the diverse perspectives offered by the framework developed and applied in this thesis's case studies. Moreover, the conceptual structure underlying the framework shows comparable traits in terms of the preparation, execution, and estimation of the parameters employed for the management of the financial risk associated with the investments examined in the case study. In order to grasp the entire operation of STEF-H2V, consult Fig. 5.4, Fig. 6.3, and Fig. 7.1, presented in the subsequent chapters, where the systematic execution of the framework is presented for each case study.

5. INTRODUCING THE VALUE-AT-RISK (VAR) RISK MEASURE TO HYDROGEN INVESTMENTS

This chapter delves into applying the Value-at-Risk (VaR) risk measure within a stochastic techno-economic framework through a Monte Carlo Simulation molded for hydrogen investments on a distributed scale. Understanding and managing risks is paramount for informed decision-making and sustainable project outcomes in the dynamic scenery of hydrogen investments.

5.1 Context setting

Water electrolysis is among the mature technologies for green hydrogen production that, when coupled with renewable electricity, represents a viable path for generating hydrogen with zero emissions [178]. Green hydrogen can be produced using different electrolysis water methods using RES. There are three principal electrolyzer technologies in water electrolysis hydrogen production: alkaline electrolytic cells (AEC), polymer electrolyte membrane cells (PEM), and solid oxide electrolytic cells (SOEC). Fig. 5.1 presents the difference between the three types of electrolyzer technologies.

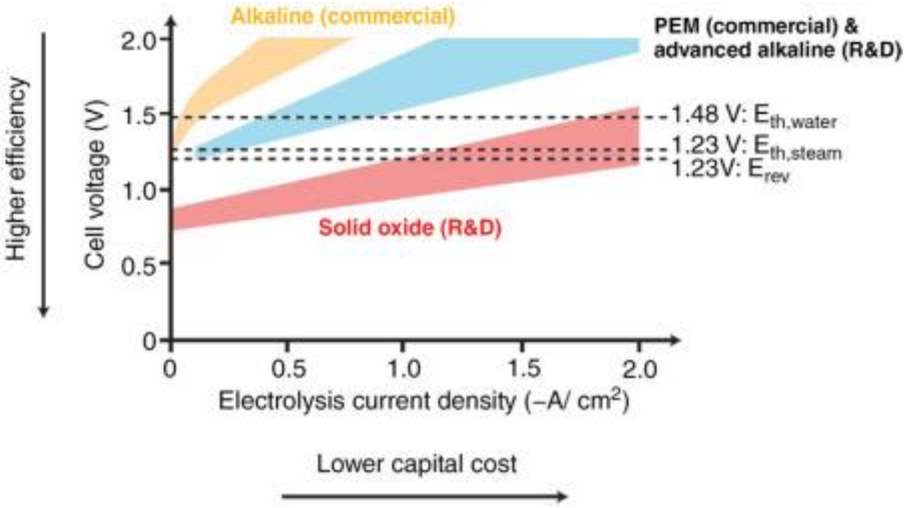

Fig. 5.1. Characteristics of AEC, PEM, and SOEC electrolyzers.

Source: [179].

The AEC is the most widely used electrolyzer because it has a lower capital cost (varying with scale), with battery life reaching 60,000–90,000 h (7–10 years) [179]. Nonetheless, the AEC has problems with aqueous electrolyte resistance and leakage, slow electrochemical kinetics, and high polarization losses (high electricity consumption) [179], [180]. AEC has a slower electrochemical reaction rate, leading to a larger effective reaction area (larger volume) if incident with PEM and SOEC for the same hydrogen production and operates at 1.8–2.4 V, greater than PEM and SOEC [179]. In addition, system efficiency (60% to 82%) and gas purity are ensured by the dynamic operation of the intermittent RES, which requires frequent starts and ramped power input [180].

PEM technology has the advantage of having a mechanism better suited to intermittent delivery of RES because of high proton conductivity and operating pressure and lower thickness and gas permeability [181]. However, the PEM electrolysis cell's lifetime is shorter than AEC's, and the system requires preprocessing water purification, which can increase the cost of hydrogen [180]. SOEC technology has a high efficiency, reaching 90% when the use of heat is included and has the potential to be economical and ecologically correct for the production of hydrogen because of its electrolyte being made of solid ion-conducting ceramics as the electrolyte, which allows operation at significantly higher temperatures with low material cost [182]. Although the minimum required SOEC voltage is less than 1.5V, the high operating temperatures present challenges in terms of material degradation and general lifetime depletion, and the mixing of hydrogen with water vapor needs additional treatment to achieve the required purity, making it commercially unavailable [180].

The selection of PEM water electrolysis was chosen for this case study as it aligns with the design of the STEF-H2V and the increasing preference for this technology in the production of green hydrogen. The practicality of green hydrogen production, as it involves a small carbon footprint, and the expected efficiency improvements of PEM electrolysis in the coming years, have sparked discussions about the decline in Levelized Cost of Hydrogen (LCOH) for its production [183], [184], [185]. Even though technologies for green hydrogen production are becoming cheaper, one should carefully explore the solar radiation and wind power behavior where the system will be installed to enhance cost-benefit. Uncertainties associated with climatic variables, among others, can influence the risk of investments in hydrogen generation systems [152], [153], [186].

In contrast to prior research, the current case study uses a methodology that integrates the Monte Carlo simulation (MCS) with a Value at Risk (VaR) technique to evaluate the LCOH across geographical regions. Typically, investments that yield the most favorable expected outcome carry a higher risk, as shown by the variance in results. This fundamental trade-off between risk and return is rooted in the principles of modern investment analysis, which posits that investors are risk-averse [67], [187]. Both the literature and the technical reports that present the LCOH for the different production routes (whether hydrogen or green hydrogen) in the different regions are commonly based only on the deterministic LCOH and, sometimes, on the average of the LCOH, without presenting further investigations into the uncertainty and risk associated with calculating the LCOH by analyzing different local potentials.

This case study proposes a stochastic approach based on the VaR-LCOH, identifying the potential for a more considerable financial risk in green hydrogen investments that only the deterministic LCOH cannot determine. The research hypothesis in this study will start from the investigation through the proposed approach (as part of a framework) in two localities with different potentials for the production of green hydrogen: Itajubá, Minas Gerais, Brazil and Cologne, North Rhine-Westphalia, Germany. One location may show a lower deterministic LCOH and a stochastic mean LCOH, but it may also show a worse pessimistic result (higher VaR-LCOH) when financial risk is considered in a robust approach.

Investment analysis for capital-intensive technologies, such as green hydrogen generation, requires careful consideration of various risks. It is crucial to evaluate potential catastrophic outcomes and the cost-effectiveness of investments in the local area or country to ensure their reliability and manageability [67], [87], [188]. This study suggests a stochastic approach that factors in local uncertainties when analyzing the levelized cost of hydrogen (LCOH) from a risk perspective. This approach differs from the traditional deterministic approach that only focuses on the mean value of LCOH. Additionally, the proposed approach includes a bias that can provide more insight into technical reports and maps regarding the feasibility of green hydrogen investments.

5.2 Case study description: distributed green hydrogen generation

This case selected two localities, one in Brazil and the other in Germany, with economic representativeness and PV potential in their respective countries. Countries have different maturation points regarding the implementation of green hydrogen systems. While Brazil still does not have large-scale production and infrastructure focused on green hydrogen, Germany already has a mature insertion of these systems in the country, where, in mid-2022, Germany already had 168 hydrogen fueling stations for urban mobility and another 43 in implementation [189]. This interface that differentiates the two countries technologically and infra-structurally conceives the justification for the locus of this study under the bias of implementing the same analysis in different realities.

PV generation has great potential in Brazil, which contributes to the generation of green hydrogen; in the place where it is least sunny in Brazil, it is possible to produce more solar electricity than in the sunniest location in Germany (see Fig. 5.2). However, solar radiation is not the only source of uncertainty and variability affecting green hydrogen investments. In this case study, five other uncertainties will be stochastically analyzed in order to present the behavior of each one of them in green hydrogen investments from a financial risk perspective. Typically, studies examine the feasibility across different regions of the world, disregarding the local uncertainties and variability sources. Such factors can change the pattern of competitiveness from one region to another regarding the expected return or financial risk for green hydrogen investments. Thus, an expected LCOH value (deterministic approach) and a VaR-LCOH (stochastic approach) will be studied in each city. From the results, the order of competitiveness will be compared for the deterministic and stochastic approaches to discuss the differences in competitiveness in each locality.

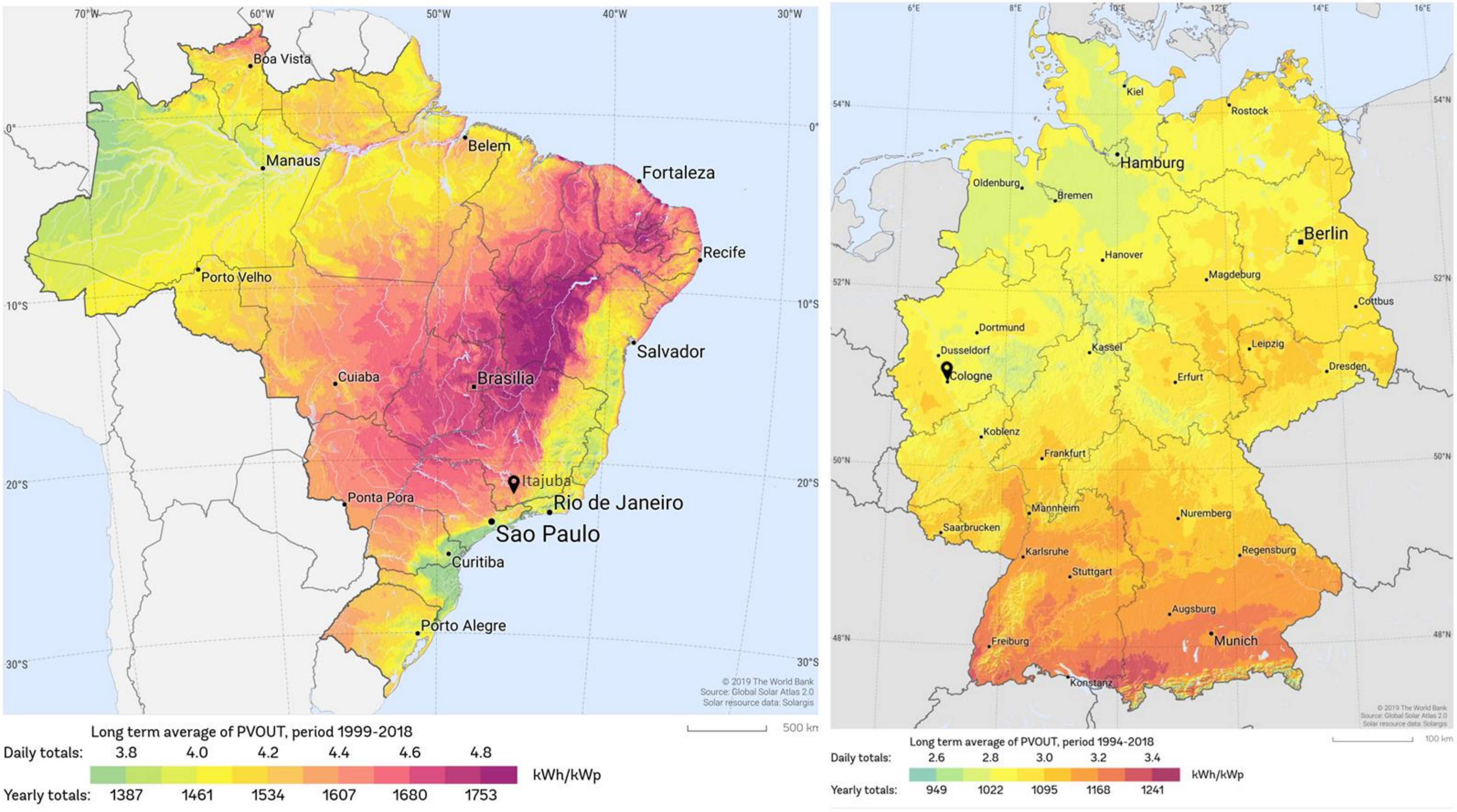

Fig. 5.2. Brazilian and German PV power potential.

Source: adapted from [190].

5.3 Basis for techno-economic analysis

The LCOH calculation considered a typical efficiency of a PEM electrolyzer (65%), and the electrolyzer's size was 1.25 MW [191], [192], so a PV plant of 2.5 MW was estimated for Itajubá and 4,2 MW for Cologne. This magnitude makes producing about 58,400 kg/year (657,000 Nm³/year). The assumed lifespan of the plant is 22 years, considering the electrolyzer's stack lifespan [191], [192]. The specifications of the electrolyzer used are shown in Table 5.1.

TABLE 5.1. ELECTROLYZER DETAILS.

Parameter	**Itajubá**	**Cologne**
Average daily solar radiation (kWh/m²)	4.99	2.94
PV system power (MW)	2.5	4.2
PV generation yearly (GWh)	3.66	3.66
Electrolyzer power (MW)	1.25	1.25
Output pressure (bar)	Up to 35	Up to 35
Electrolyser overall efficiency (%)	65	65
Hydrogen Production (kg/h)	20	20
Stack lifetime (h)	65,000	65,000
Electrolyzer electricity consumption (kWh/kg)	60	60
Water consumption (m³/h)	0.34	0.34
Plant lifetime (year)	22	22
Daily operation time (h/day)	8	8
Compression system power (W)	500	500
Compression flow (kg/h)	5.09	5.09
Compressor electricity consumption (kWh)	0.5	0.5
Storage capacity (day)	3	3

The analysis did not consider loan payments (for debt investment) or debt interest. In addition, non-cash deductions (i.e., depreciation and amortization) are also disregarded. Thus, the CAPEX is obtained through Eq. (5.1):

$$CAPEX_T = CAPEX_{PV} + CAPEX_{El} + CAPEX_{Co} + CAPEX_{St} \tag{5.1}$$

where: $\mathrm{CAPEX_{El}}$ is the investment cost that refers to the electrolyzer system obtained by the electrolyzer power (1.25 kW) multiplied by the purchase cost of the electrolyzer in US$ per kW (1000 US$/kW) [193]; $\mathrm{CAPEX_{Co}}$ is the investment cost in the compression system found by multiplying the number of compressors needed by the price of each compressor (130k US$) [194], where the number was obtained by dividing the total annual flow of the plant by the hourly flow of the compressor (rounding up); $\mathrm{CAPEX_{St}}$ is the storage capital cost achieved by the number of storage days multiplied by the storage cost (63 US$) [195].

$CAPEX_{PV}$ is the investment cost of the PV system, and $CAPEX_{PV}$ is obtained by the investment price per Wp in the installed power unit (0.77 US$/Wp in the Brazilian [196] and 0.8 US$/Wp in the German [197]), multiplied by the PV cell power (345 Wp) and by the number of PV cells necessary to supply the plant demand. Technical data of a PV cell were considered, with the following parameters: Rated Power (P) = 345 Wp; η = 21% (efficiency); A = 1.63m2 (area); δ = 0.25% per year (degradation rate) [198].

The yearly historical series (1985–2021) regarding the irradiation values from Itajubá and Cologne were extracted from the Power Data Access Viewer [199], using the average local irradiation (4.99 kWh/m² for Itajubá and 2,94 kWh/m² for Cologne). Fig. 5.3 shows each city's yearly irradiation means (kWh/m^2). It is important to emphasize that the amount of irradiation also affects the CAPEX since a lower expected amount means more PV cells are required to gather individual demands.

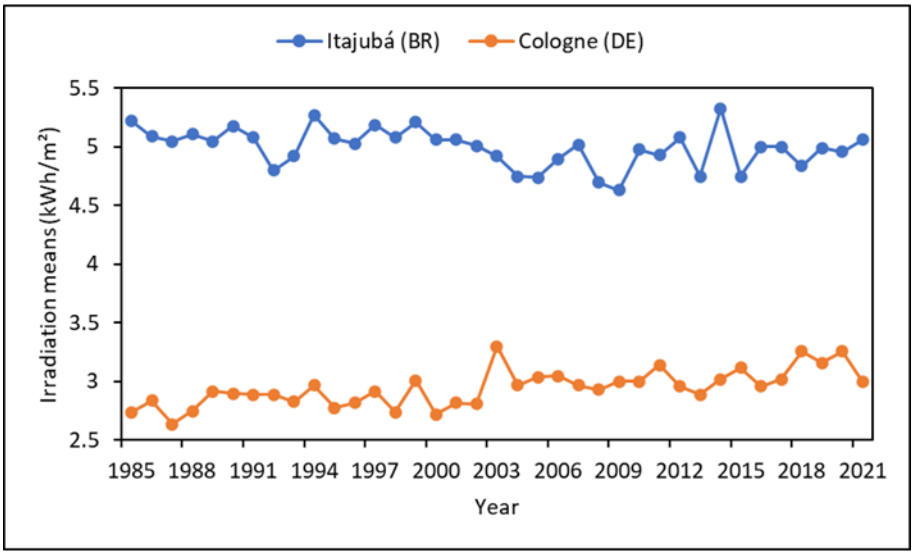

Fig. 5.3. Yearly irradiation average in Itajubá and Cologne.

Similarly to the CAPEX, one should consider the OPEX, which refers to operating expenses, as expressed in Eq. (5.2):

$$OPEX_n = OPEX_{PV} + OPEX_{El} + OPEX_{Co} + OPEX_{St} \tag{5.2}$$

where: $OPEX_{PV}$ = the operating cost of the renewable system; $OPEX_{El}$ = composed of the O&M cost added to the cost of water and electricity consumption and replacing the electrolysis stack if it reaches its useful life; $OPEX_{Co}$ = compressor OPEX; and $OPEX_{St}$ is the storage system OPEX.

Notably, there may or may not be a variable cost related to replacing the electrolysis stack over its lifetime. Remarkably, the values expressed in Brazilian currency (Real) were converted to US dollars (BRL to USD) using an exchange rate of 1.00 USD to 5.00 BRL, and €1 is equivalent to 1.05 USD. The input cost data used for estimating LCOH are summarized in Table 5.2.

TABLE 5.2. INPUT PARAMETERS USED FOR CALCULATING LCOH.

Parameter	**Note**	**Itajubá**	**Cologne**	**Source**
Solar PV price (US\$/Wp)	The total system cost, including the balance of the system (BOS)	0.77	0.84	[196], [200]
PV OPEX (US\$)	% of the PV system CAPEX	0.5	1.0	[200], [201], [202]
PEM electrolyzer CAPEX (US\$/kW)	Includes stack and BOS	1000	1000	[193], [200]
PEM electrolyzer OPEX (US\$)	% of the PEM electrolyzer CAPEX	2	2	[200], [203]
Stack replacement cost (US\$/kW)	Stack lifetime = 65000 h @ full load for PEM electrolyzer	400	400	[193], [200]
Water Cost (US\$/m³)	Based on local companies	2.43	3,15	[200], [204]
Electricity Cost (US\$/kWh)	Local tariffs for each city were assumed	0.25	0.42	[205], [206]
Compressor CAPEX (US\$)	Unit price	1,300 k	1,300 k	[194]
Compressor OPEX (US\$)	% of the Compressor CAPEX	0.8	0.8	[194]
Storage CAPEX (US\$/ Nm³)	Storage days multiplied by the storage cost	63	63	[195]
Storage OPEX (US\$/day)	% of the Storage CAPEX	0.5	0.5	[207]
Discount rate (%)	Based on each country	10.5	4	[197], [208]

Investments in green hydrogen production vary according to electrolyzer technology, renewable system technology for electricity generation (wind or solar), plant size, geographic region, and climate conditions. In solar green hydrogen systems, electrolyzer CAPEX depends highly on scale, with price tiers covering the system's total cost, including electrolyzer stack, plant balance (BoP), installation, civil works, grid connection, and utilities. Capital investments represent the most significant portion of the total costs over the lifetime of the system and comprise expenses with electrolyzer battery; auxiliary equipment of the electrolyzer system; hydrogen compression and storage system; PV modules and inverters; cables and protectors; civil works, engineering costs, and interconnection and commissioning costs [209], [210]. In contrast, the OPEX throughout the system's lifespan pertains to the operational and maintenance costs associated with the electrolytes, PV system, and hydrogen compression and storage systems [75], [170].

Regarding the performance of solar hydrogen production using PV electrolysis, it is significant to emphasize that the current and voltage depend on the incidence of solar radiation that reaches the equipment [211]. Therefore, the level of local solar radiation is the determining variable for performing electricity [212] since the efficiency of PV panels varies with the intensity of solar radiation and ambient temperature, making it a significant metric to calculate the efficiency of the PV system and the hydrogen production system [170]. In this way, the higher solar radiation levels increase the efficiency of both systems and the production of green hydrogen. Eq. (5.3) describes the estimated PV electricity generation:

$$PV_{eg} = \eta * \rho * A * (1 - \gamma) * (1 - \delta^{n-1}) \tag{5.3}$$

where: η is the PV cells efficiency (percentage); ρ is the local irradiation (kWh/m^2); A is the occupation area by the system (m^2); γ is the system losses (≈19% [213]), and δ is the degradation factor per year, 0.25% [67].

Electrolysis units based on PEM electrolysis technology have a high potential for cost reductions and efficiency improvements because of technological advances [210], [214]. PEM electrolyzers offer greater flexibility in terms of modulation range and response time, and they are a compact design that works with higher current densities, which makes them a suitable candidate for use with renewable energies, known for their intermittent generation. (e.g., solar energy) [178], [214], [215]. The green hydrogen is obtained in kg or Nm^3 (101.325 kPa and 0 °C) related by constant density in normal conditions equal to 0.0898 kg/Nm^3 [178], and its annual production through PEM electrolysis can be calculated using Eq. (5.4) [149], [170]:

$$G_{H2} = \frac{t * P_{El} * u}{E_{El}} (1 - \delta)^{n-1} \tag{5.4}$$

where: G_{H2} stands for the generation of green hydrogen; t is the sum of hours in the year (h); P_{El} is the power of the electrolyzer (kW); u is the utilization rate of the electrolyzer expressed in a fraction; E_{El} represents the electricity consumption of the electrolyzer (kWh/kg); δ is the system degradation rate per year (2% [216]), and n is the year.

This study estimates LCOH using a stochastic approach (based on Monte Carlo Simulation). Uncertainty and variability will be inserted in six assumptions: annual solar irradiation, which represents a significant uncertainty in the production of renewable energy; the price of the PV system per Wp; system utilization rate; system efficiency; electrolyzer price per kW and the discount rate (based on previous studies [67], [101], [143], [149], [166], [168], [177], [217]). In this way, the mathematical calculation of stochastic LCOH by Monte Carlo simulation can be described by:

$$\widetilde{LCOH} = f\left(\widetilde{TOTEX}, \widetilde{G_{H2}}, \tilde{r}\right) \tag{5.5}$$

where: $\widetilde{LCOH}$ = probability distribution for the LCOH outputs from the simulations; $\widetilde{TOTEX}$ = probability distribution for total cost values (TOTEX) obtained through iterations with random values of the PDFs assigned to the PV system price, electrolyzer price, and discount rate; $\widetilde{G_{H2}}$ = probability distribution for green hydrogen production values, obtained from iterations with random PDF values appointed to yearly solar irradiation, system utilization rate, and system efficiency; $\tilde{r}$ = PDF assigned to the discount rate.

5.4 Input simulation assumptions

The procedure behind the framework described was explicitly developed to examine the complexities that encompass uncertainty, variability, and risk in green hydrogen investments. Unlike most studies that use simple sensitivity analyses (deterministic methods using point or expected values) to estimate LCOH for hydrogen production systems, this analysis employs a probabilistic method to assess the effects of technical and economic uncertainties and variability on the green hydrogen production costs under a risk perspective. The technical-economic stochastic framework used in this study incorporates a Monte Carlo approach to reproduce uncertainty and variability in the levelized cost of hydrogen. Fig. 5.4 presents a diagram of the framework used in this case study.

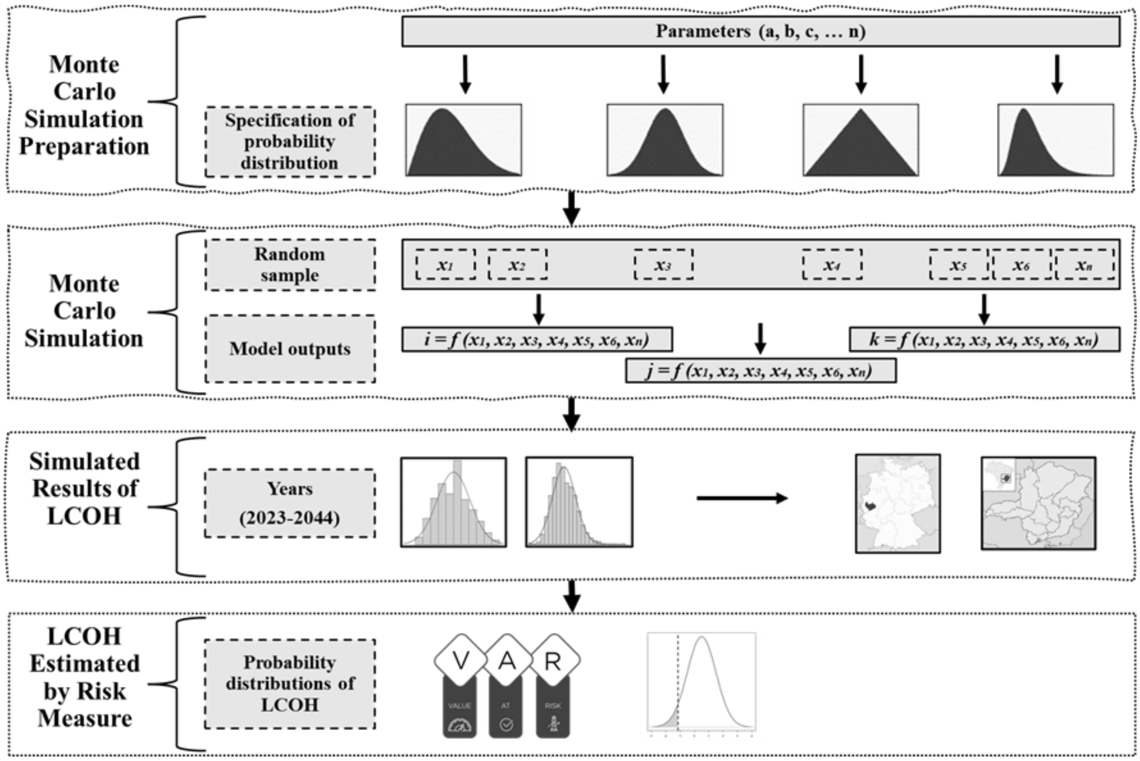

Fig. 5.4. STEF-H2Voverview with Monte Carlo Simulation to estimate LCOH.

In the initial step of Fig 5.4, probability distributions are specified for key input parameters and variables within the framework. These distributions represent the range of potential values and their likelihood of occurrence. Parameters such as production costs, energy prices, and operational efficiencies are assigned probability distributions based on historical data, expert knowledge, or other relevant sources (see Table 5.3). This preparation phase sets the stage for the Monte Carlo simulation by defining the uncertainty around input variables.

Subsequently, the Monte Carlo simulation is conducted through the generation of a significant quantity of random samples derived from the designated probability distributions of input variables (5000 MSC interactions [218], [219], [220]). Each sample represents a potential scenario or combination of parameter values. These samples are then inputted into the model, and the model is run repeatedly to produce a corresponding set of output values. By aggregating the results of multiple runs, the Monte Carlo simulation provides a comprehensive understanding of the range of potential results and their associated probabilities.

The simulated results of the LCOH involve applying the Monte Carlo simulation results to estimate the levelized cost of hydrogen (LCOH) for 2023 to 2044 at Itajubá and Cologne. The LCOH represents the total cost of hydrogen production over the project's lifecycle, normalized to a standard unit (per kilogram). By simulating LCOH values across multiple years and locations, the analysis captures variations in cost drivers and market conditions, providing insights into hydrogen production's economic viability and competitiveness.

The MCS used six input parameters to delve into the sources of uncertainty impacting the levelized cost of hydrogen for green hydrogen investments from a financial risk standpoint. These input parameters were characterized by six probability distribution functions employed to estimate the LCOH and VaR-LCOH. The input parameters included the electrolyzer cost, daily utilization rate, system efficiency, average daily solar radiation, solar PV price, and discount rate, as seen in Table 5.3.

TABLE 5.3. PROBABILITY DISTRIBUTION ASSUMPTIONS.

	Variable	**Probability Distribution**
Itajubá	Electrolyzer Cost (US$/kW) [1]	Beta-PERT (500; 1164.8; 2097.6)
	Daily utilization rate (h)	Triangular (6.5; 8.0: 9.5)
	System Efficiency (%)	Triangular (52; 65; 78)
	Mean daily solar radiation (kWh/m²)[2]	Weibull (4.24; 0.82; 5.27709)
	Discount rate (%)	Triangular (8.4; 10.5; 12.6)
	Solar PV price (US$/kW)	Triangular (0.62; 0.77; 0.92)
Cologne	Electrolyzer Cost (US$/kW)	Beta-PERT (500; 1164.8; 2097.6)
	Daily utilization rate (h/day)	Triangular (6.5; 8.0; 9.5)
	System Efficiency (%)	Triangular (52; 65; 78)
	Mean daily solar radiation (kWh/m²)	Weibull (2.54; 0.45; 2.68921)
	Discount rate (%)	Triangular (3.2; 4.0; 4.8)
	Solar PV price (US$/kW)	Triangular (0.67; 0.84; 1.01)

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[1] Based on [149].

[2] Goodness-of-fit is executed based on Anderson Darling's test at Crystal Ball® to check the best distributions for each location.

In this final step, the probability distribution of the LCOH obtained from the Monte Carlo simulation is employed to estimate the Value-at-Risk (VaR) for LCOH. VaR represents the maximum potential loss at a specified confidence level within a given time horizon. By analyzing the probability distribution of LCOH, VaR-LCOH identifies the threshold level of LCOH beyond which the probability of incurring significant losses becomes significant. This approach provides valuable insights for decision-makers, enabling them to effectively assess and manage the financial risks associated with hydrogen investments.

5.5 Techno-economic results and discussion remarks

This study presents the results of the TEA, while the discussion focuses on the developments of LCOH in Brazil and Germany, considering uncertainty and financial risk. Initially, there is a potential presence of the 2023 LCOH levels for the 1.25MW PEM electrolyzer systems powered by PV systems. Therefore, the LCOH calculations are executed using the MCS technique, followed by the estimation of VaR-LCOH using the probability distributions of LCOH obtained during the simulations. Additionally, this section compares the LCOH distributions and the values obtained from the deterministic calculations. Finally, it examines the sensitivity and risk analysis findings to identify the key factors responsible for financial risks in green hydrogen investments in Brazil and Germany.

5.5.1 Deterministic analysis

The initial estimation involved calculating the deterministic LCOH for each country's locality. Table 5.4 lists the expected present value of TOTEX (CAPEX plus OPEX), the expected solar irradiation of each city, the present discounted value of green hydrogen production during the system lifetime (Present Expected $G_{H2}*$), and the deterministic result for LCOH.

TABLE 5.4. LCOH DETERMINISTIC RESULTS.

	Itajubá	**Cologne**
PV panels (No.)	7,251	12,292
TOTEX (Million US$)	4.554	7.192
Expected average daily ρ (kWh/m^2)	4.99	2.94
Present Expected $G_{H2}*$ (kg)	458,896	752,072
Deterministic result for LCOH (US$/kg)	9.92	9.56

The initial observation concerning the deterministic outcomes is the disparity in TOTEX values between Brazil and Germany. Given the disparities in PV generation potential, increasing the number of PV modules is imperative to fulfill a minimum daily demand of 10,020 kWh in the initial year of operation. In this way, it was possible to confirm that the variation of solar irradiation influences both the level of electricity production and the production of green hydrogen and the present value of costs during the system's useful life. The TOTEX composed of CAPEX and OPEX becomes greater in places with lower irradiation levels, as higher costs with solar cells are required. At Cologne, CAPEX comprises 81% of costs and OPEX 19%. At Itajubá, CAPEX reaches 92%, and OPEX is only 8%. The higher OPEX value of the PV system in Cologne contributes significantly to its representation in terms of OPEX. This is primarily because of the need for a larger number of PV modules to meet the demand and the utilization of a higher rate of PV OPEX compared to Itajubá, as specified in Table 5.2.

Regarding the deterministic results of LCOH, Cologne in Germany appears to be the most competitive location for investments in green hydrogen systems compared to Itajubá in Brazil. This is an unexpected result since the photovoltaic potential in Itajubá is almost twice as high as Cologne's. However, this result can be justified by the different discount rates offered in the two countries. In Germany, the discount rate is lower than in Brazil, which justifies a lower LCOH. This aspect is highly relevant for investments in green hydrogen, as it is observed that besides the PV potential, financial indicators such as the discount rate affect the economic sustainability of projects in renewable systems.

5.5.2 Stochastic analysis and descriptive statistics

Considering the uncertainties, the MCS is undertaken to accurately estimate the variables and potential endogenous arising from these stochastically simulated uncertainties. The LCOH values were evaluated through 5000 Monte Carlo simulations, incorporating the uncertainties characterized by the probability distributions outlined in Table 5.3. This methodology generated a dataset of 5000 LCOH values, and then the VaR-LCOH was determined at a 95% confidence level, which seemed appropriate for assessments related to renewable systems [221], [222], [223]) for each respective location. Fig. 5.5 illustrates the probability distribution of estimated LCOH for the green hydrogen project in Itajubá and Cologne. In contrast to single-point estimates in the deterministic case, the range of outcomes represents the inherent uncertainty of investment, offering a comprehensive method for evaluating the economic feasibility of a project.

Its geographic location heavily influences the LCOH of a green hydrogen production system. This can be attributed to the direct relationship between the electrolyzer utilization rate and the capacity factor of the renewable electricity generation system. Additionally, the varying utilization rates of the electrolyzer at different locations, caused by climatic conditions, introduce more significant uncertainty in investment analyses.

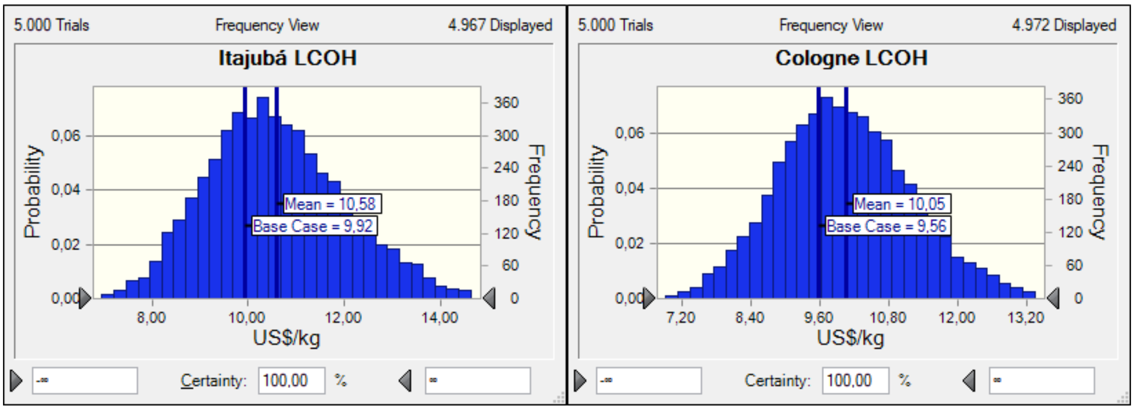


Fig. 5.5. LCOH probability density at Itajubá and Cologne.

The results of the stochastic analysis (still without investigating the financial risk) show more favorable conditions for producing green hydrogen in Germany, even though its PV solar potential is lower than in Brazil. At Cologne, the average LCOH is US$10.05/kg, and at Itajubá, US$10.58/kg, with a US$0.53 difference. Exemplarily relating to the deterministic results, it is possible to observe that the LCOH at Itajubá increased by 6.2%, going from US$9.92 to US$10.58. At Cologne, the difference for the deterministic case was 4.9%, with an increase in stochastic LCOH of US$0.49. These disparities affect the decision-making procedures in green hydrogen endeavors. The LCOH probability density functions do not differ only in terms of their average estimates. Table 5.5 presents the main statistics of the stochastic analysis, where further details can be discussed.

TABLE 5.5. MCS STATISTICS FOR THE LCOH.

Statistics	**Cologne LCOH**	**Itajubá LCOH**
Trials	5000	5000
Base Case	9.56	9.92
Mean	10.05	10.58
Median	9.99	10.46
Standard Deviation	1.17	1.44
Variance	1.37	2.08
Skewness	0.2950	0.4071
Kurtosis	3.04	3.06
Coeff. of Variation	0.1163	0.1363
Minimum	6.92	6.96
Maximum	14.60	16.16
Range Width	7.68	9.20
Mean Std. Error	0.02	0.02

The analysis of Table 5.5 reveals that Itajubá exhibits higher standard deviation and variance, suggesting increased uncertainties and hidden risks associated with investment in this specific project. The coefficient of variation statistic compares forecast variability between LCOHs, even when their forecast scales differ. This can be attributed to the independence of the statistics from the units used in the forecasting process. Thus, it should be noted that the LCOH at Itajubá demonstrates a significantly higher absolute variability than the LCOH at Cologne, with a difference of 2%. This further underscores the importance of using risk metrics in TEA.

Describing the LCOH curves (see Fig 5.5 and Table 5.5) statistically, concerning kurtosis (peakedness), both LCOH distribution curves show very similar behavior with kurtosis values slightly higher than 3. Thus, it is inferred that these curves are faintly leptokurtic (meaning peaks) compared to the normal distribution, which is often used as a reference standard and has a kurtosis of 3 [224]. Hence, it can be deduced that both curves show a distinct sharpness, presenting a softly steep slope at their apex, signifying an overall balanced distribution of LCOH values, albeit with specific values exhibiting notable highs or lows.

Specifically, it is possible to analyze the behavior of the skewness coefficient for both cases, where one can observe that the distribution of LCOH in Itajubá has a more significant skewness than in Cologne. However, it is potential to infer that both LCOH distributions are symmetrical for having their skewness coefficients between -0.5 and 0.5, justifying the use of VaR [225], [226]. Although symmetrical, it is also possible to observe that the Itajubá LCOH distribution, because of its more positive skewness coefficient, illustrates a positive skewness distorted “to the right,” where most of the LCOH values are close to the minimum LCOH, although these may be higher than Cologne's LCOH.

5.5.3 Sensitivity analysis

Additional insights for the stochastic LCOH are provided through a sensitivity analysis, visualized in Fig. 5.6 (the center line indicates the LCOH estimate). The sensitivity charts show each assumption's influence on a detailed LCOH forecast. The sensitivity chart displays these rankings as a bar graph, showing which assumptions are the most or least important in this analysis. The factors that drive the risk and their due relevance are represented by how much the average LCOH value estimates change when a single input is varied within its predefined range. Awareness of the drivers contributes to better risk management of any investment in green hydrogen. Note that the assumption of average daily solar radiation was grouped since this parameter was simulated in all years of the lifetime of each project.

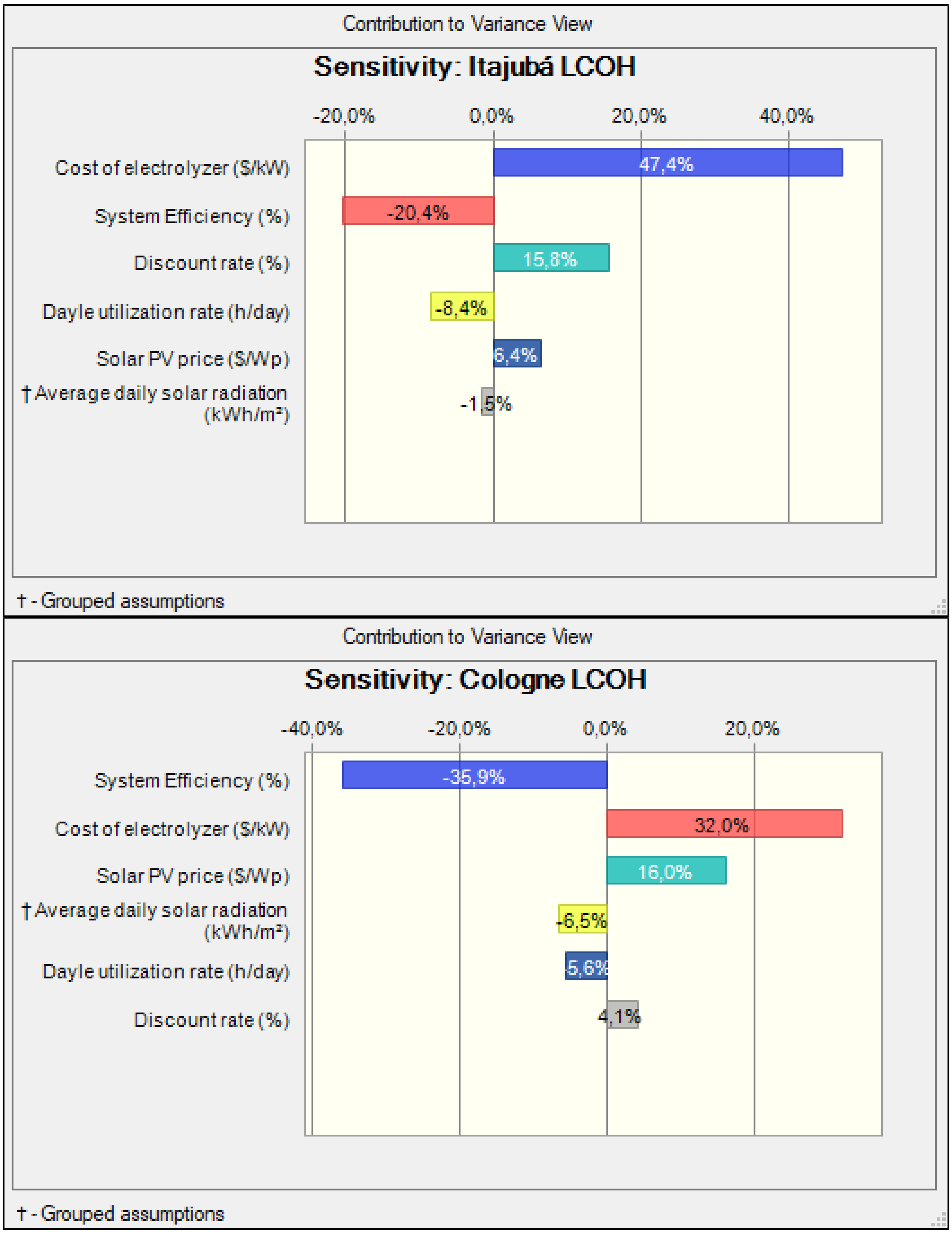


Fig. 5.6. Key cost drivers affecting the LCOH at Itajubá and Cologne.

Fig. 5.6 presents the sensitivity analysis results for each location's green hydrogen production, where the sensitivity data is shown as horizontal bars to the right and left of the 0 lines, showing the magnitude and direction of the LCOH sensitivity (interpreted as the percent of LCOH variance because of each assumption). Fig. 5.6 shows the six assumptions (uncertainty) that significantly impact the output cell regarding LCOH for green hydrogen investments. The “Cost of Electrolyzer,” “Discount Rate,” and “Solar PV Price” variables positively impact LCOH performance for both localities, and “System Efficiency,” “Daily Utilization Rate,” and “Average Daily Solar Radiation” have a negative impact. Although ranked in different positions, that behavior shows how regional aspects affect investments in this technology and how investors and decision-makers should manage uncertainty when investing in local green hydrogen production.

This sensitivity analysis discusses the nuances of the assumptions assumed when calculating LCOH. On the right side of Fig. 5.6, it is possible to observe the variables' behavior in the LCOH forecast at Itajubá, where the “Cost of Electrolyzer” accounts for approximately 47.4% of the variance in the LCOH performance and can be considered the most significant assumption, followed by the “System Efficiency” with a coefficient 20.4% negatively affecting the variance. Occupying third and fourth place, respectively, are the "Discount Rate" (contributing around 15.8% to the LCOH forecast variance) and the "Daily Usage Rate," with approximately -8.4%. Last, contributing less to the LCOH variance is "Solar PV Price" with 5.4% and "Average Daily Solar Radiation" with adverse effects on investment performance (-1.5%). Analyzing the forecasting behavior of LCOH at Cologne, the findings show differences in how uncertainties affect investments in green hydrogen. In Colonia (Germany), there is a change in the ranking of assumptions when compared to Itajubá (Brazil), in which "System Efficiency" becomes the most significant variable in the LCOH forecast and is also the most important, with approximately 35.9%. The "Cost of Electrolyzer" goes to the second position to forecast variance (around 32%). In third and fourth place, respectively, are "Solar PV Price" (approximately 16% for LCOH forecast variance) and "Average Daily Solar Radiation," approximately -6.5%. A lesser amount of the LCOH variance appears in the "Daily Utilization Rate" with -5.6% (adverse effects on the performance) and the "Discount Rate" (only 4.1% for the forecast variation of the LCOH).

The importance of accounting for endogeneities between assumptions is exemplified by Fig. 5.7, which exposes how the uncertainties are related to the LCOH forecast in both case studies. In Brazil, the “Cost of Electrolyzer” is undoubtedly the substantial uncertainty associated with investing in green hydrogen because water electrolysis technology is still evolving, and its commercial use may vary according to resource availability, government policies, and market demand. It is also important to mention the imports of water electrolysis technology, which may include the importation of electrolytic cells, balancing systems, electronic components, and other equipment necessary to implement the technology, contributing to the intensification in the cost of technology in Brazil. Analyzing the German side, the “Cost of Electrolyzer” did not prove to be as expressive in predicting LCOH as in Brazil. However, this assumption was only below "System Efficiency," which appeared as the most important, with about four percentage points above the “Cost of Electrolyzer.” Analyzing the European scenario, Germany had almost half of the hydrogen filling stations on the continent, accounting for 111 out of 223 [189], showing the country has a robust and well-structured policy for developing the hydrogen economy and its value chain. Cologne and its surroundings have four hydrogen refueling stations with an average demand of 17.28 kg/day [189].

As already mentioned, solar radiation levels in Brazil are better than in Germany for photovoltaic generation, and this may be one aspect that made this assumption have a lower impact on the uncertainty of LCOH at Itajubá since the country already has a very high index. In the case of Germany, there was a contrasting scenario, as the "Average Daily Solar Radiation" played a more significant role in calculating LCOH. Although "Average Daily Solar Radiation" was not the most expressive assumption in both sensitivity analyses, it has a stochastic nature that imposes a series of complexities on green hydrogen systems because of its management difficulty. In this case study, this assumption is considered a source of variability (see Table 5.3) inherent in the system, which is impossible to ignore or eliminate as it describes a phenomenon with different values and unpredictability. In analyses that compare several locations in the same region or country for the evaluation of investments, solar radiation can be a more expressive assumption, allowing it to identify and rank the places with investment potential [67], [149].

After presenting the sensitivity chart, scatterplots are provided to communicate the results as a function of stochastic LCOH. This spotlight shows simulation application with investment analysis to show correlations, dependencies, and other relationships between LCOH and assumptions. Fig. 5.8 uses the assumptions in Table 5.3 to analyze the variability in LCOH based on the variability in each of the six factors.

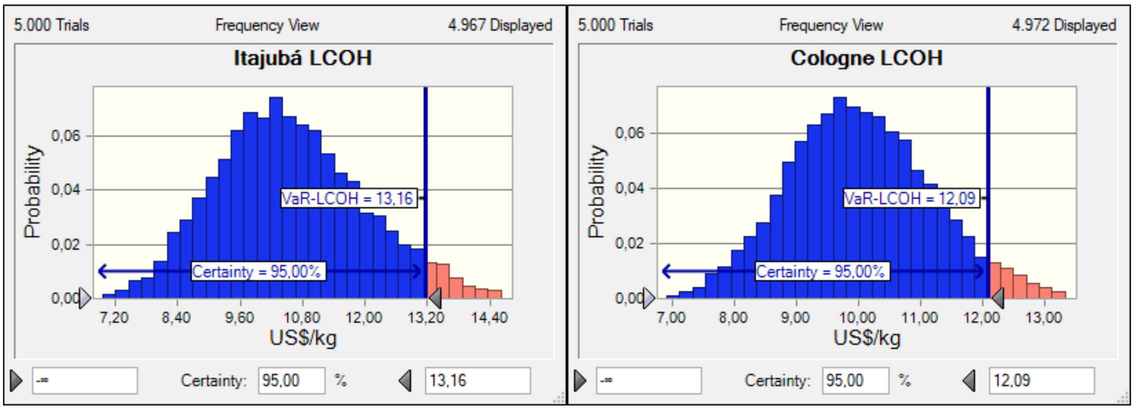
Fig. 5.7 contains the plots of LCOH mapped against the set of secondary variables (assumptions) for Itajubá and Cologne. Each chart displays a point cloud aligned on a grid within the scatterplot window, showing the set of all analysis assumptions plotted against the LCOH prediction. The correlation analysis results for each place quantify the agreement between each LCOH input and output parameter on a scale of -1 to +1, stating that the closer the points are to the line, the closer the relationship among the plotted variables will be. Slanted lines from lower to higher values (bottom left to top right) show positive relationships and a positive correlation shows that a higher value for the input parameter will cause a higher LCOH. If the relationship is negative, the line slopes from higher to lower values (upper left to lower right), and in a negative correlation, a lower value for the input parameter will rise in a higher LCOH.

Fig. 5.7. Scatter chart with correlations from LCOH to Itajubá and Cologne.

The “Cost of Electrolyzer” assumption has a strong positive correlation (0.6618 for Itajubá and 0.5434 for Cologne) with LCOH, a relationship verified by also the sensitivity graph (see Fig. 5.7), in which the line in each graph shows where the paired points would appear if sorted in ascending order. Secondarily, the "System Efficiency" assumption has the highest negative correlation with LCOH (-0.5995 for Cologne and -0.4548 for Itajubá), showing the importance of efforts to improve efficiency in electrolysis systems, opening a potential path for a future cost reduction [183], [184], [185], [210], [214]. The lowest correlation is the "Average Daily Solar Radiation" for the Itajubá case (around -0.0993), and the "Discount Rate" with approximately 0.174 (Cologne). This insight shows that the discount rate practiced in Germany is already at a reasonable level for investments in green hydrogen, which differs from Brazil, where the "Discount Rate" presented a positive correlation of 0.3699, placing it in the third position of the assumptions that most affect the LCOH forecast.

5.5.4 Risk analysis using VaR

Through an approach that considers uncertainties, it is possible to compare the risk and VaR in the lifetime period in this analysis. Fig. 5.8 contains the VaR-LCOH for the analyzed localities presented graphically by the MCS.



Certainty: 95,00 % 13,16

Certainty: 95,00 % 12,09

Fig. 5.8. VaR-LCOH estimate at Itajubá and Cologne.

Fig. 5.8 shows that the Itajubá has the highest value for VaR-LCOH, as in the other cases of LCOH. In brief, according to the VaR-LCOH charts, there is a 5% chance that the LCOH value exceeds US$13.16 for Itajubá and US$12.09 for Cologne. The concept of LCOH implies that the investment viability decreases as the cost increases, making it an essential indicator of cost-effectiveness. When LCOH exceeds the selling price of green hydrogen, the project cannot be considered a feasible investment. Hence, the VaR-LCOH analysis is conducted on the distribution curve's extreme right tail, representing the most unfavorable expected LCOH values.

The disparity in VaR-LCOH between Cologne and Itajubá is significantly remarkable compared to the disparities between the two localities for deterministic and stochastic LCOH values. The deterministic LCOH difference between Cologne and Itajubá was US$0.36. When observed from the side of the stochastic approach, this difference between the LCOHs was US$0.56, showing the importance of considering uncertainties and how they affect the analysis of investment in green hydrogen. Considering the financial risk perspective, the differences in VaR-LCOH between the localities amounted to US$1.07. By comparing the deterministic and stochastic results of LCOH, Cologne experiences an increase of US$512 thousand, while Itajubá sees an increase of US$735 thousand. This shows how neglecting uncertainties can significantly affect the viability of investments in green hydrogen.

This analysis provides valuable insights for investors and decision-makers as it informs information regarding the investment potential of green hydrogen projects, specifically regarding uncertainty and risk associated with the levelized cost. Although analyzed under a pessimistic bias for the highest value using The VaR-LCOH values, when examined with a pessimistic approach to assess the highest value using VaR, it exceeds the values stated by Badgett et al. [80] for electrolysis PEM (around US$5-6/kg) and remains below US$2/kg for SM. However, it was possible to find values close to those obtained by stochastic analysis in the literature, both for more and for less, considering similar technologies and a stochastic approach with uncertainties [76], [149], [166], [175], [176], [177]. Besides its investment analysis, this case study shows the impact of uncertainties and risk within a stochastic approach on investment analysis of green hydrogen. By presenting evidence that goes beyond deterministic calculations, this analysis provides a comprehensive understanding of the subject.

5.6 Summary of results and analysis

The present study aimed to stochastically analyze the economic potential from the VaR-LCOH approach to investigate the financial risk of investments in green hydrogen, which the deterministic LCOH presented in the literature cannot identify from the uncertainty perspective. A comparative analysis was conducted between Brazil and Germany based on the differences between the risk classification of VaR - LCOH and deterministic LCOH. The results revealed that even in localities with high renewable energy potential, the risk of investing in green hydrogen could differ significantly, which does not occur from a deterministic perspective.

According to cost estimates for investments in Brazil and Germany, the LCOH estimates align closely with most previous studies on LCOH using the same production technologies. Several unique parameters determine the investment's economic viability. The main concentration is reducing the capital expenditure linked to electrolysis technology, which will cause a decrease in the overall investment outlay for the project. Conversely, the efficiency of the electrolyzer emerged as a significant factor in the investment analysis, causing technological enhancements.

Brazil's PV potential raises secondary concerns regarding financial risk, with the discount rate being a key factor. Nevertheless, adopting investment strategies for green hydrogen production can effectively address these concerns. In Germany, a contrasting scenario unfolds, as the nation already implements a green hydrogen investment policy with a helpful discount rate for such investments. However, because of its photovoltaic potential, more photovoltaic modules are needed to supply the electricity demand used by the electrolyzer. Thus, the price of the PV system (US$/Wp) appears as a variable that secondarily deserves attention in the analysis of financial risk in investments of green hydrogen that is essentially manageable.

When considering and evaluating the financial risk in green hydrogen investments, a statistically significant difference can be observed in the VaR-LCOH estimate, approximating the investment risk between Brazil and Germany, which can be changed by managing the assumptions. This discussion makes room for the importance and role of financial risk analysis and characterization, clarifying points about investment costs that, surprisingly, may not be considered by investors and decision-makers in investment analysis. Additionally, this case study examines the role of economic incentives in the viability and sustainability of green hydrogen investments from the perspective of uncertainty and financial risk analysis, using a novel probabilistic approach with VaR, encouraging stakeholders in the sector to engage in discussions on this topic.

6. EXPLORING THE GAP IN TECHNO-ECONOMIC ANALYSIS FOR GREEN HYDROGEN INVESTMENTS

This chapter applies the framework from a holistic perspective to integrate financial risk management into techno-economic analysis, assuming financial risk indicators in the assessment. In the current era of sustainable energy transition, a deep understanding of the complex relationship between financial risk and techno-economic analysis can provide helpful insights to augment decision-making processes within the expanding green hydrogen sector.

6.1 Introductory perspective

Renewable hydrogen stands at the front of the global energy transition, assisting as a valuable key for sustainable and carbon-neutral solutions [227]. Nations and industries are attempting to reduce their carbon footprint and combat climate change, demanding clean and renewable resources [228]. In this context, hydrogen produced from renewable sources such as wind and solar has emerged as a versatile and promising energy carrier with the potential to transform multiple sectors, including transportation, industry, and power generation.

Investments in infrastructure and technology have experienced a notable increase as the demand for renewable hydrogen continues to grow [229]. However, while there is great potential for renewable hydrogen, it is essential to acknowledge and tackle the complex challenges associated with its widespread adoption and deployment. One particular challenge, commonly overlooked, involves effectively managing the financial risk associated with investments, especially when it has a capital-intensive character. Despite the considerable potential for growth and innovation, renewable hydrogen projects are not immune to financial uncertainties, market fluctuations, and regulatory complexities, which can significantly impact their viability and long-term success [230], [231], [232].

Techno-economic analysis has long been recognized as a crucial tool for evaluating renewable energy projects' technical and economic feasibility, including those involving hydrogen production and utilization [233], [234]. By systematically assessing factors such as capital costs, operational expenses, energy efficiency, and market dynamics, TEA provides valuable insights to evaluate the attributes and the potential return of energy technologies. Nevertheless, traditional TEA rarely considers the complex financial aspects that drive investment decisions, as it cannot recognize the inherent financial risks that can profoundly affect project outcomes. Neglecting this aspect can cause unforeseen risks and challenges for investors and policymakers, compromising renewable hydrogen investments' financial feasibility and long-term viability [188].

These obstacles highlight the importance of integrating comprehensive financial risk management practices into TEA frameworks for green hydrogen investments. By incorporating sophisticated risk assessment methodologies, scenario analysis, and sensitivity testing, stakeholders can better understand the financial implications and uncertainties surrounding green hydrogen projects [235], [236]. Consequently, this allows for more informed decision-making, risk management, and optimization of investment strategies within the dynamic field of renewable energy finance [237], [238].

This chapter explores the intersection of renewable hydrogen investment and financial risk management, bridging the gap between these critical domains. Through a combination of theoretical insights, practical case studies, and strategic recommendations by integrating financial risk assessment measures into TEA, this study can empower stakeholders with the knowledge and tools needed to explore the complexities of green hydrogen investments effectively.

6.2 Case study description: integrating financial risk management into TEA

This study addresses a stochastic approach under uncertainty and risk for the Brazilian scenario of large-scale production of green hydrogen considering solar-generated electricity through PV-electrolysis. The target point is filling the gap in TEA for green hydrogen investments integrating the financial risk assessment into a comprehensive case study conducted in eight Brazilian states, based on the data availability: Bahia (BA), Ceará (CE), Minas Gerais (MG), Paraíba (PB), Pernambuco (PE), Piauí (PI), Rio Grande do Norte (RN) and São Paulo (SP). Fig. 6.1 shows the average solar PV generation (in average MW, i.e., MW_{avg}) for the number of plants in the eight states in this study and the average capacity factor for each month from 2018 to 2023.

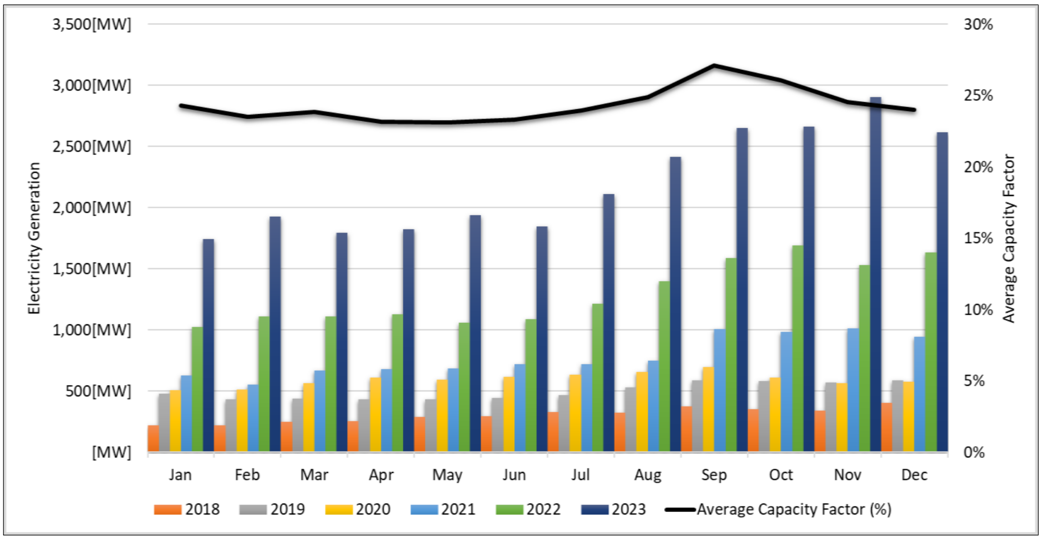


Fig. 6.1. Solar generation and monthly capacity factor (MW_{avg}).

Source: derived from [239].

The context of green hydrogen in Brazil is influenced by a confluence of factors, including the country's ample renewable energy resources, ambitious decarbonization goals, and strategic positioning in the global energy landscape. Brazil has a vast expanse of land and coastline with abundant solar and wind resources, displaying great potential for renewable energy generation, particularly from solar PV and wind farms (see Fig. 6.2). Pushed by the pressure to reduce greenhouse gas emissions and transition towards a low-carbon economy, green hydrogen has emerged as a decisive element of Brazil's energy transition strategy with hubs in development around the whole country [240], [241].

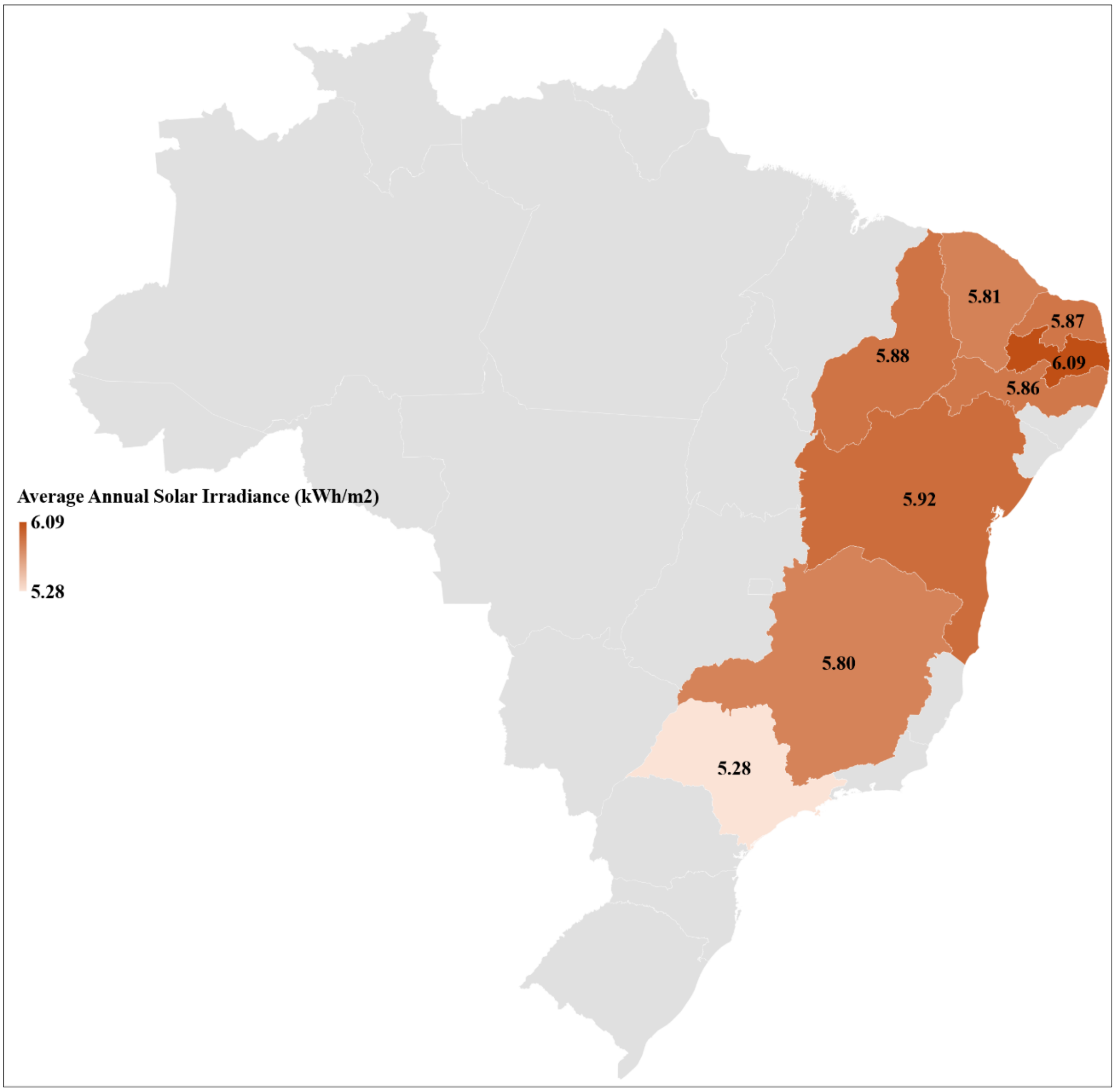


Fig. 6.2. Brazilian states and its solar potential (1882-2022).

Source: derived from [199].

6.3 Techno-economic considerations

This study investigates the potential of investments in green hydrogen employing financial indicators (WACC, CAPM, and LCOH) and risk measures (VaR and Omega ratio) as financial indicators associated with cost and risk, stochastically simulated. Thus, it will be possible to compare whether the results of the financial risk stochastic approach can provide more valuable information than a deterministic analysis. By considering uncertainties and financial indicators associated with risk in the analyses, decision-makers can access reliable data. Therefore, identifying risks in green hydrogen projects becomes essential for new investments to be trustworthy since green hydrogen plants have a capital-intensive character.

The techno-economic analysis in the case study is established in Fig. 6.2, employing the most current and comprehensive version of STEF-H2V thus far. The first consideration is estimating the electricity generation from a Solar PV system within a hydrogen production system, which involves a meticulous process that integrates various parameters and considerations. Solar PV technology plays a fundamental role in renewable energy systems, particularly those aimed at hydrogen production via PEM electrolysis, since the electricity generated by Solar PV panels serves as a clean and sustainable energy source to power the electrolysis process, converting water into hydrogen and oxygen. Eq. (5.3) provides an outline of the essential factors that must be considered when assessing solar production via PV electrolysis:

$$PV_g = \eta * \rho * A * \gamma * (1 - \delta^{n-1}) \tag{5.3}$$

where: η denotes the PV cells efficiency (percentage); ρ refers to the local irradiation (kWh/m^2); A represents the occupation area by the system (m^2); γ denotes the performance ratio (81%), which considerate the losses, and δ stands the subsequent annual power degradation factor, 0.4% [242].

This estimation process is fundamental for evaluating green hydrogen production's performance and economic feasibility within the Solar PV system. The choice of utilizing the PEM electrolyzer technology is based on its capability to achieve a more significant "turndown" from full power, usually ranging from 10 to 20% of maximum power. Furthermore, the PEM technology is prominent for its efficiency, reduced environmental impact, and faster dynamic response to changes in input, which contributes significantly to enhancing the overall system's capacity to handle the intermittent nature of solar PV sources [181], [186]. The mass of green hydrogen production is evaluated using Eq. (6.1):

$$m_{H2} = \frac{t * u * P_{El}}{E_{El}} (1 - \delta)^{n-1} \tag{6.1}$$

where: m_{H2} represents the generation of green hydrogen; t is the sum of hours in the year (h); u is the utilization rate of the electrolyzer linked to the local Solar PV capacity factor (%); P_{El} denotes the electrolysis system power (kW); E_{El} embodies the total electricity usage of the electrolyzer system (kWh/kg); δ is the degradation rate, and n is the amount of hours operated by the electrolyzer in a year.

The LCOH plays a critical metric for assessing the economic viability of green hydrogen systems, encompassing all costs associated with hydrogen generation over the system's lifetime. Estimating LCOH involves a comprehensive analysis of several considerations, such as capital expenditures, operational costs, replacement costs, efficiency, and feedstocks used in hydrogen production. By quantifying the cost per unit of hydrogen produced over its entire lifecycle, LCOH provides valuable insights into the competitiveness of hydrogen technologies and informs strategic decision-making in the transition towards a sustainable hydrogen economy. The LCOH is quantified in US$/kg and is valued in today's money using Eq. (5.3):

$$LCOH = \frac{CAPEX + \sum_{n=1}^{N}\left(\frac{OPEX_n + REPEX_n}{(1+r)^n}\right)}{\sum_{n=1}^{N}\left(\frac{m_{H2}}{(1+r)^n}\right)} = \frac{TOTEX}{\sum_{n=1}^{N}\frac{m_{H2}}{(1+r)^n}} = \frac{Total\ Lifetime\ Cost}{Total\ Lifetime\ Hydrogen} \quad (6.2)$$

where: CAPEX represents the capital expenditure that is incurred at the beginning of the project, year 0 (US$); OPEX is the operational expenditure (embodies the operation and maintenance costs), which is typically considered occurring at the end of each year, from year 1 to the end of the project lifetime; REPEX characterizes the replacement expenditure of the system components across the system lifespan; TOTEX denotes the total expenditure related to the costs that result from the sum of CAPEX and discounted OPEX and REPEX (US$); n = system lifetime; r = discount rate based on the stochastic WACC and CAPM approaches (%); m_{H2} = green hydrogen discounted generation (kg) in period n.

The CAPEX, OPEX, and REPEX have been estimated for the entire system, which includes the Solar PV and electrolyzer system. This estimation considers the replacement of both the electrolyzer stack and the inverter of the solar PV system. These last two expenditures are discounted because they will happen in the future, in year n, and are estimated as proportional to CAPEX. In order to calculate the LCOH, it is necessary to equate the present value of the lifetime costs with the present value of the lifetime hydrogen generation, as demonstrated in Eq. (6.2).

Meanwhile, the stochastic LCOH is mathematically calculated as:

$$\widetilde{LCOH} = f\left(\widetilde{TOTEX}, \widetilde{m_{H2}}, \tilde{\imath}\right) \quad (5.5)$$

where: $\widetilde{LCOH}$ = probability distribution function (PDF) for the LCOH outputs from the simulations; $\widetilde{TOTEX}$ = probability distribution function for total cost (TOTEX) obtained via iterations with random values of the PDFs related to the PEM capital cost, PV capital cost, PEM OPEX, yearly solar irradiation, and exchange rate; $\widetilde{m_{H2}}$ = probability distribution function for green hydrogen production values, obtained from iterations with random PDF values appointed to the stack efficiency, stack degradation rate, utilization, $\tilde{\imath}$ = probability distribution function of the WACC (interest rate) generated via iterations with random values of the PDFs assigned to the inflation rate.

Integrating financial risk management into green hydrogen techno-economic analysis involves the structure of an approach that encompasses uncertainty and variability associated with hydrogen production costs. In the LCOH stochastic context, this approach can apply the MCS to estimating the VaR and Omega ratio. The STEF-H2V examines the complexities that encompass uncertainty, variability, and risk in green hydrogen investments, employing a probabilistic model using MCS to assess the effects of technical and economic uncertainties and variability on green hydrogen production costs from a risk perspective. The procedure behind the framework developed in this analysis is presented in Fig. 6.3.

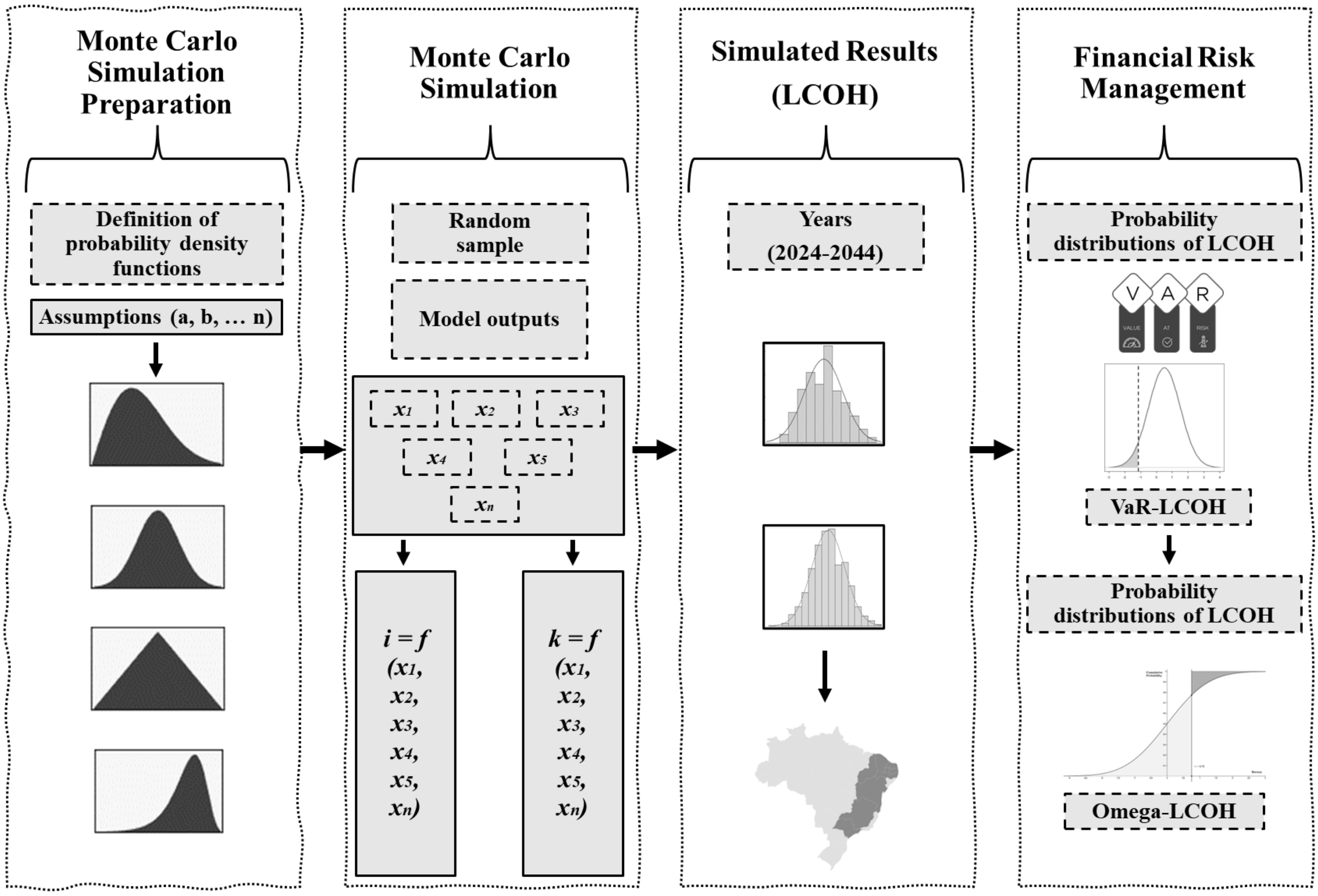


Fig. 6.3. Framework overview in this case study.

The Monte Carlo simulation on STEF-H2V involves four key steps that consider the specific context of hydrogen production in Brazilian states, providing more contextualized information. The preparation step involves identifying and gathering data on parameters influencing hydrogen generation costs, such as capital expenditures, operating expenses, efficiency metrics, and external factors like solar irradiation and input prices.

In order to generate multiple system scenarios, the simulation step applies a random sample of the specified PDF for each parameter. These samples were then propagated through the LCOH calculation model to estimate LCOH values for each scenario. In order to adjust for uncertainty in the assumptions, this procedure is iterated ten thousand times, thereby producing a spectrum of LCOH values that encompasses the array of potential outcomes. Following the Monte Carlo simulation of hydrogen production in Brazilian states between 2024 and 2054, the resulting LCOH values for each state are presented as a probability distribution, which allows for further analysis using descriptive statistics. This analysis provides valuable insights into the feasibility and cost competitiveness of hydrogen production across various regions and timeframes in Brazil.

Financial risk management techniques are applied in this final phase using the simulated LCOH distribution. Probability distributions of LCOH values are analyzed to calculate risk measures, such as Value at Risk (VaR-LCOH). VaR-LCOH represents the maximum potential loss of LCOH with a specified confidence level over the simulation period, helping stakeholders understand the downside risk associated with hydrogen production investments. Omega-LCOH measures the probability-weighted average return relative to the VaR-LCOH threshold, providing insights into the risk-return profile of hydrogen production investments and guiding financial risk management strategies.

6.4 Key components

The basis for the techno-economic analysis in the case study is based on Fig. 4.2, where the STEF-H2V is employed in its most current and comprehensive version so far. The first consideration for this case study is the system data, which includes all the technical parameters and data related to renewable energy systems and their components, such as PV systems and electrolysis systems. These parameters are crucial for understanding the technical aspects and performance of the systems, especially when dealing with investments in renewable energy, which is essential to gather precise and comprehensive system data to make accurate evaluations of feasibility.

The solar PV specifications serve as the foundational component, dictating the specifications and capabilities of the Solar PV energy generation system. Key parameters, such as PV Cell Efficiency, PV Panel Area, and PV Panel Power, dictate the solar energy conversion efficacy. Environmental factors such as Temperature and Heat Loss Coefficient, and operational metrics, such as the Performance Ratio and PV Panel Degradation Rate, substantiate the nuanced analysis of PV system performance. Moreover, the Electrolysis System Power, encompassing attributes like Cell Voltage, Active Area, and Stack Lifetime, underscores the criticality of electrolyzer efficiency in hydrogen production. Stack Efficiency, Stack Electricity Usage, and Output Pressure intricately delineate electrolysis systems' operational dynamics and productivity. Table 6.1 presents each key parameter related to the system data in the framework.

TABLE 6.1. SYSTEM DATA PARAMETERS.

Parameter	**Description**
Electrolysis system power	Electrolysis system power represents the electrical power input required to operate a hydrogen production system based on water electrolysis. It is critical for assessing hydrogen generation's energy efficiency and operational costs.
Cell voltage	Cell voltage refers to the electrical potential difference across the electrodes of an electrolysis cell during the electrolysis process. It is a key parameter for controlling the electrolysis reaction and determining hydrogen production rates.
Cell active area	Cell active area represents the surface area of the electrodes within an electrolysis cell where the hydrogen and oxygen gases are produced. It influences the efficiency and productivity of the electrolysis process.
Stack lifetime	Stack lifetime denotes the electrolysis stack operational lifespan, which comprises multiple individual cells (operating conditions, materials degradation, and maintenance practices influence it).
Stack efficiency (LHV)	Stack efficiency, expressed as a percentage of the lower heating value (LHV) of hydrogen, quantifies the energy efficiency of an electrolysis stack in converting electrical energy into hydrogen gas. It reflects the ratio of actual hydrogen production to the theoretical maximum output based on electrical input.
Stack electricity usage (LHV)	Stack electricity usage denotes an electrolysis stack's electrical energy consumed during hydrogen production, calculated based on hydrogen gas's lower heating value (LHV). It represents the electrical input required to drive the electrolysis process.
Stack degradation rate	Stack degradation rate represents the rate at which the performance of an electrolysis stack deteriorates over time due to factors such as material degradation, catalyst poisoning, and operating conditions. It influences the long-term efficiency and reliability of hydrogen production systems.
Output pressure	Output pressure denotes the pressure at which hydrogen gas is delivered from the electrolysis system. System design, operating parameters, and application requirements determine it.
PV cell efficiency	PV cell efficiency quantifies the ability of solar cells to convert sunlight into electricity. It is a percentage representing the ratio of usable electrical power output to incident solar radiation.
PV panel area	PV panel area refers to the total surface area occupied by photovoltaic panels or solar modules within a solar energy system. It is a key parameter for determining the system's energy generation capacity and spatial requirements.
PV panel power	PV panel power represents the maximum electrical power output of a photovoltaic panel or solar module under standard test conditions. The efficiency and size of the solar cells within the panel determine it.
PV panel degradation rate	The PV panel degradation rate represents the rate at which the performance of photovoltaic panels deteriorates over time. It is typically expressed as a percentage reduction in efficiency per year.
Performance ratio	The performance ratio quantifies a solar photovoltaic system's overall efficiency and performance by comparing the actual energy output to the theoretical maximum output under standard test conditions. It is influenced by shading, soiling, and system losses.
Panel number	Panel number denotes the total quantity of photovoltaic panels or solar modules installed within a solar energy system. It directly influences the system's energy generation capacity and spatial requirements.

(CONTINUA)

Parameter	Description
Total area PV system	The total area of a PV system represents the cumulative surface area occupied by all photovoltaic panels or solar modules within a solar energy system. It encompasses the aggregate spatial footprint of the PV array.
PV power system	PV system power denotes the total electrical power output of a photovoltaic solar energy system. It is determined by factors such as the number and efficiency of solar panels, solar irradiance, and system losses.

In the LCOH calculation, the electrolyzer's power was assumed to be 100MW, considering the typical efficiency of a PEM electrolyzer (66.1% LHV), and the production nameplate capacity was estimated between 12,257 kg/day and 8,688 kg/day [243], [244], with a PV power plant estimated around 111-156 MW and depends on the solar radiation and the capacity factor for each state. The plant is expected to last for 30 years. The estimation of the solar PV system incorporated technical data displaying the subsequent characteristics: Nominal max. power (Pmax) = 720 Wp; Module efficiency = 23.2%; Dimensions = 3.11 m2; Degradation = 0.4% per year [245]. The electrolyzer system information is provided in Table 6.2.

TABLE 6.2. PEM ELECTROLYZER DATA.

Parameter	Value
Electrolysis system power	100 [MW]
Cell voltage	1.9 [V]
Cell active area	700 [cm^2]
Stack lifetime	61,320 [hours]
Stack efficiency (LHV)	66.10%
Total electricity usage (Stack + BOP)	33.31 [kWh/kg]
Stack degradation rate	1.5%
Output pressure	300 [psi]

SOURCE: [243], [246], [247], [248].

Multifaceted assumptions delineating projects' economic viability and sustainability are embedded in green hydrogen investments' financial aspects. Financial parameters and assumptions are listed, including exchange rates, capital costs, electricity prices, inflation rates, and tax considerations. These financial assumptions are essential for conducting economic analysis and evaluating the financial viability of the investment. In Brazil, the tariffs for utilities such as water and electricity differ among the states, with data sourced from the local utility companies in each respective state [249], [250], [251], [252], [253], [254], [255], [256].

STEF-H2V integrates financial risk management into TEA, incorporating both CAPM and WACC in the analysis to enhance the framework's reliability. These two models deal with financial modeling aspects, helping to determine the required rate of return for the investment and assessing the cost of capital. In order to incorporate a discount into the projected values of hydrogen generation and OPEX over the system's lifespan, a discount rate (r) was calculated based on the WACC, as outlined in Equation (2.1), with the cost of equity for WACC determined using the Capital Asset Pricing Model (CAPM), as detailed in Equation (2.2). The parameters for estimating the discount rate are determined using the market values of the Brazilian market in February 2024, and Table 6.3 brings essential inputs for conducting financial modeling, risk assessment, and investment analysis.

TABLE 6.3. FINANCIAL ASSUMPTIONS.

Parameter	**Value**	**Ref.**	**Remarks**
Inflation rate	4.50%	[257]	The inflation rate reflects the annual percentage change in the economy's general price level of goods and services. It is a critical factor for adjusting financial projections, costs, and revenues over time to account for changes in purchasing power.
Exchange Rate	$5.00	[258]	This parameter represents the prevailing exchange rate between the United States Dollar (USD) and the Brazilian Real (BRL). It is crucial for financial modeling and decision-making in green hydrogen projects, particularly for assessing costs and revenues denominated in different currencies.
PEM capital cost	$1650.00/kW	[259]	PEM capital cost refers to the initial capital expenditure required for procuring and installing a proton exchange membrane (PEM) electrolysis system for hydrogen production. It encompasses costs associated with equipment, materials, labor, and installation.
PV capital cost	$0.53/kWp	[260]	PV capital cost represents the upfront investment required for establishing a photovoltaic (PV) solar energy system in Brazil. It includes solar panels, mounting structures, inverters, balance of system components, and installation expenses.
Water price	$2.61/m^3 – $15.77/m^3	Based on state tariff	Water price links to the cost of water required for hydrogen production through electrolysis or other industrial processes. It includes water sourcing, treatment, distribution, and disposal expenses and differs according to the state of Brazil.
Fixed O & M (% of installed CapEx PV)	0.5%	[188]	Fixed Operation and Maintenance (O&M) costs as a percentage of installed Capital Expenditure (CapEx) for PV systems refer to the ongoing expenses associated with operating and maintaining photovoltaic solar energy systems, expressed as a percentage of the initial investment in PV infrastructure.
Fixed O & M (% of installed CapEx PEM)	5.0%	[243]	Fixed O&M costs as a percentage of installed CapEx for PEM electrolysis systems represent the ongoing operational and maintenance expenditures for hydrogen production facilities, expressed as a percentage of the initial investment in electrolyzer equipment and infrastructure.
Beta	0.57	[261]	Beta (β) measures an asset's volatility or sensitivity to market movements relative to a benchmark such as the overall market. It is used in financial modeling and investment analysis to assess the systematic risk associated with an asset or portfolio.
Levered Beta	1.11	[261]	Levered Beta (β↑) represents the adjusted beta of a leveraged company or investment, accounting for the impact of debt financing on the asset's risk profile. It is used in financial valuation and risk assessment to account for the effects of financial leverage on equity returns.

(CONTINUA)

Parameter	**Value**	**Ref.**	**Remarks**
Risk-free rate	11.53%	[262]	This parameter refers to the theoretical return on an investment with zero risk of financial loss, generally represented by the yield on government bonds or treasury securities. It is a benchmark for evaluating investment returns and discounting future cash flows in financial analysis.
Market risk premium	8.60%	[263]	The market risk premium ($r_m – r_f$) represents the additional return investors expect to receive above the risk-free rate to compensate for bearing systematic risk in the stock market. It reflects the equity risk premium and is used in the CAPM to estimate expected investment returns.
Capital Asset Pricing Model	21.08%	Simulated by Eq. 2.2	The CAPM is a financial model used to estimate the expected return on an investment based on its systematic risk. This model considers the risk-free rate, market risk premium, and beta coefficient of the asset to calculate the cost of equity capital.
Debt Ratio	58.58%	[261]	The debt ratio represents the proportion of a company's financing provided by debt relative to its total capital structure. It is evaluated by dividing total debt by assets and serves as a measure of financial leverage.
Equity Ratio	41.42%	[261]	The equity ratio characterizes the proportion of a company's financing provided by equity relative to its total capital structure. It is calculated by dividing total equity by total assets and reflects the ownership stake of shareholders in the company.
Income Tax	34%	[264]	Income tax refers to the taxes imposed on the taxable income of individuals or entities by governmental authorities. It is a significant financial modeling and investment analysis consideration, affecting after-tax cash flows and profitability.
Cost of Debt	9.67%	[265]	The cost of debt refers to the interest rate or yield paid by a company on its debt financing, such as bonds, loans, or credit facilities. It represents the cost of borrowing funds and is a key component of WACC calculation.
Cost of Equity	21.08%	Based on CAPM	The cost of equity embodies the expected rate of return demanded by investors for providing equity financing for a company. The cost of equity can be calculated using the CAPM and reflects the opportunity cost of investing in the company's equity shares compared with alternative investments of similar risk.
Weighted Average Cost of Capital	9.47%	Simulated by Eq. 2.1	WACC is a financial metric representing a company's average cost of financing, considering the proportional weights of debt and equity in its capital structure. It is calculated as the weighted average of the cost of debt and the cost of equity, adjusted for tax effects.

Before estimating the hydrogen system, it is important to understand the utilization of diverse energy sources and resources. Understanding the balance between feedstock use and output is crucial for assessing renewable hydrogen production systems' overall efficiency, cost-effectiveness, and environmental sustainability, maximizing the system's productivity. In the operational field, the utilization of feedstocks, including stack and BoP (Balance of Plant) electricity usage, alongside water consumption, delineates the operational dynamics and resource utilization efficiency, which are essential inputs for renewable hydrogen production through electrolysis. The estimation of the feedstock considered the use of 50.4 kWh/kg for the electricity supplied to the electrolyzer stack for the electrolysis process, 5.0 kWh/kg for the electricity consumed by the BoP components, which support the operation of the electrolyzer system but are not directly involved in hydrogen generation, and 0.014 m^3/kg of water required for the electrolysis process [243], [246], [266]. These components illustrate the energy and resource requirements for hydrogen generation, highlighting the crucial role of electricity and water in the electrolysis process.

A key aspect in evaluating the techno-economic feasibility of green hydrogen investments is estimating system characteristics and performance metrics throughout its operational lifetime. The system estimation in the framework provides essential parameters, such as the system lifetime (30 years for this study) and the utilization, which is linked to the capacity factor of the renewable system used to provide electricity for the electrolysis process. The utilization of the electrolyzer system in this case study is determined by assessing the solar PV capacity factor for each state using this important parameter as an assumption (uncertainty) in the stochastic simulation by data from National Electric Systems Operator (ONS, its acronym in Portuguese) [267]. For [266], the capacity factor is a dominant factor in hydrogen production cost, directly impacting the system utilization and, subsequently, the magnitude of the LCOH. Electrolysis systems with high capital costs need to be operated at high-capacity factors to achieve the lowest LCOH, and when capital cost decreases, the LCOH occurs at lower-capacity factors [266]. This part of the analysis can provide crucial insights into the operational dynamics and replacements, resource requirements, and performance metrics of the renewable hydrogen production system, facilitating comprehensive analysis and informed decision-making.

Planning for component replacements within renewable hydrogen systems is essential for maintaining operational efficiency and prolonging the system's lifespan. Parameters such as inverter replacement for Solar PV systems and stack replacement for electrolyzers denote the practical maintenance strategies essential for sustaining system performance over time. The inverter replacement indicates the percentage of the solar PV capital expenditure (CapEx) allocated for the replacement since inverters are an essential component of PV systems that convert DC electricity generated by solar panels into AC electricity suitable for grid use. The portion of the initial investment allocated for replacing inverters over time, either due to deterioration and damage or technological obsolescence, is denoted by 15% and occurs every ten years to help in scheduling maintenance activities or budgeting for replacement costs [260], [268]. The portion of the initial investment designated for replacing electrolyzer stacks is 15% and occurs every seven years for the electrolyzer system due to degradation or other factors [243], [246], [266]. Electrolyzers are a notable component in a hydrogen plant that uses electricity to split water into hydrogen and oxygen, and the stack is a critical element within them.

In Monte Carlo simulation, key components serve as assumptions or inputs that define the characteristics and behavior of the system being modeled. These components can represent a wide range of factors, such as physical properties and economic variables characterized by PDF, depending on the dynamics of the simulation. These assumptions are fundamental in estimating the LCOH, as they enable modeling the complex dynamics of hydrogen production systems and account for the range of potential LCOH outcomes, considering the associated uncertainty and variability in hydrogen production costs. Table 6.4 presents the breakdown of each assumption and its associated PDF.

TABLE 6.4. ASSUMPTIONS PDF.

Assumption	Type	PDF	Proxy	Description
Solar irradiation	Physical	Weibull (4.73; 1.27; 7.42) BA Weibull (5.21; 0.68; 2.93) CE Weibull (3.96; 2.10; 2.72) MG Weibull (5.72; 0.40; 3.27) PB Weibull (5.51; 0.37; 2.57) PE Weibull (5.38; 0.54; 2.46) PI Weibull (5.25; 0.67; 5.85) RN Weibull (4.61; 0.73; 4.54) SP	Goodness-of-fit based on Anderson Darling's test at Crystal Ball® by data from [199].	Solar Irradiation represents the annual amount of solar energy available at the location, influencing electricity generation.
Utilization	Physical	Normal (28.4; 4.6) BA Normal (25.86; 3.94) CE Weibull (18.66; 7.62; 2.26) MG Weibull (4.50; 18.87; 4.23) PB Weibull (9.61; 12.38; 2.25) PE Normal (23.02; 5.78) PI Normal (23.76; 4.95) RN Normal (20.27; 3.91) SP	Goodness-of-fit based on Anderson Darling's test at Crystal Ball® by data from [267].	Utilization refers to the percentage of time the electrolyzer operates at full capacity.
Stack Efficiency	Technical	Triangular (60.2; 66.1; 72.0)	Based on expert judgment, flexibility, and ease of interpretation to model uncertainty.	The PEM electrolyzer stack's efficiency determines electricity's conversion efficiency into hydrogen.
Stack degradation rate	Technical	Triangular (0.5; 1.5; 2.5)	Based on expert judgment, flexibility, and ease of interpretation to model uncertainty.	Over time, PEM electrolyzer stacks may experience degradation, reducing their efficiency and increasing operating costs.

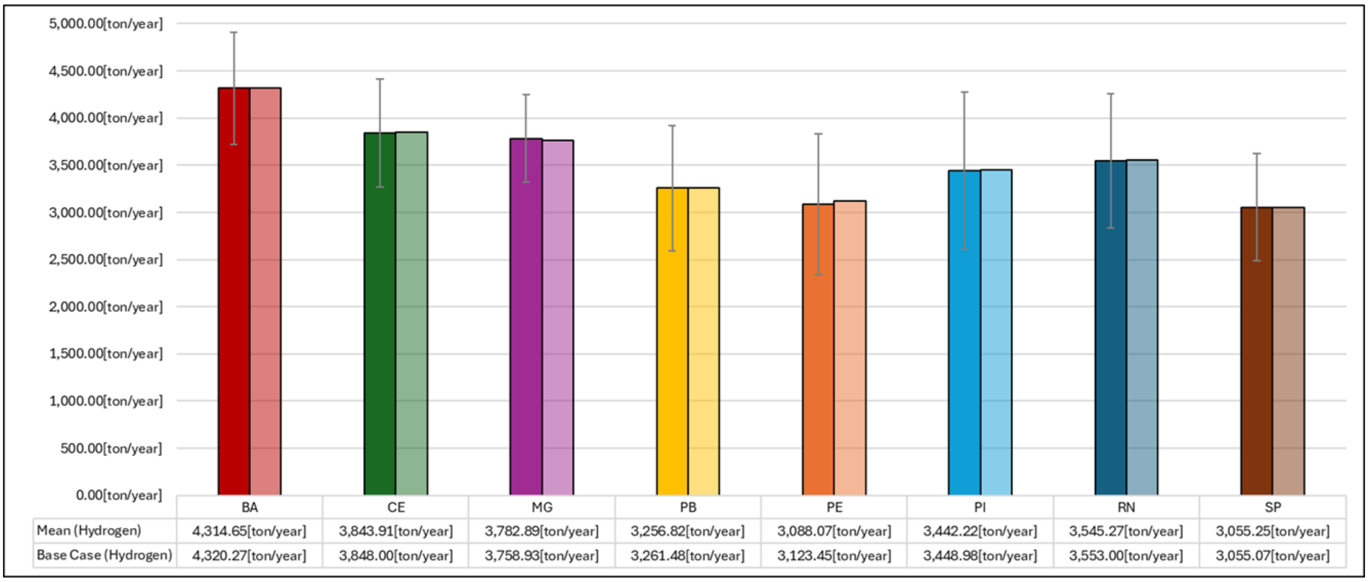
(CONTINUA)

Assumption	**Type**	**PDF**	**Proxy**	**Description**
Exchange rate	Financial	Minimum Extreme (5.24; 0.36)	Goodness-of-fit based on Anderson Darling's test at Crystal Ball® by data from [269].	Exchange rate fluctuations become a crucial factor influencing the cost of equipment or materials.
Inflation rate	Financial	Gamma (3.07; 2.53; 1.46)	Goodness-of-fit based on Anderson Darling's test at Crystal Ball® by data from [257].	The inflation rate affects the future value of costs and revenues associated with the project.
PEM capital cost	Economic	Beta PERT (1,200; 1,650; 2,100)	Based on [149], [188].	PEM capital cost represents the initial investment required to buy and install the equipment necessary for hydrogen production.
PV capital cost	Economic	Beta PERT (1.30; 2.65; 4.00)	Based on [149], [188].	PV capital cost refers to the initial investment needed for the solar PV system, which generates electricity for the electrolyzer.
PEM OpEx	Economic	Triangular (2.0; 5.0; 8.0)	Based on expert judgment, flexibility, and ease of interpretation to model uncertainty.	PEM electrolyzer OpEx encompasses ongoing costs such as maintenance, labor, and water consumption

6.5 Analysis and discussion remarks

6.5.1 Hydrogen production

A total of 10,000 simulations were executed to analyze the LCOH outcomes for each Brazilian state after the arrangements in the framework, considering diverse regional perspectives. The initial analysis in this study is related to hydrogen production, with particular emphasis on the assumption of the simulations allocated to the stack efficiency, stack degradation rate, and utilization. This factor encompasses inherent uncertainty and is crucial for estimating the potential hydrogen generation using the electricity provided by the PV systems, which directly impacts the variability of the sunlight amount available for conversion into electricity across different regions.



	BA	CE	MG	PB	PE	PI	RN	SP
Mean (Hydrogen)	4,314.65[ton/year]	3,843.91[ton/year]	3,782.89[ton/year]	3,256.82[ton/year]	3,088.07[ton/year]	3,442.22[ton/year]	3,545.27[ton/year]	3,055.25[ton/year]
Base Case (Hydrogen)	4,320.27[ton/year]	3,848.00[ton/year]	3,758.93[ton/year]	3,261.48[ton/year]	3,123.45[ton/year]	3,448.98[ton/year]	3,553.00[ton/year]	3,055.07[ton/year]

Fig. 6.4. Hydrogen production by state.

For comparison, the average hydrogen production and standard deviation were used in the stochastic approach to capture variation in hydrogen production in each approach.

The base case (deterministic) represents each state's estimated hydrogen production capacity under standard conditions. Bahia has the highest hydrogen production capacity at 4,320.27 tons/year, significantly higher than other states. São Paulo, on the other hand, has the lowest production capacity at 3,055.07 tons/year. This variation is due to differences in the availability of resources for hydrogen production across the states. The mean values reflect the average hydrogen production capacity, showing the central tendency of the production with values very close to the base case values, with Bahia again leading the highest mean value, while São Paulo remains the lowest. This consistency reinforces the reliability of the framework estimates across different scenarios. However, the differences that appear could impact the hydrogen cost and will be explored later.

Regarding the standard deviation measurement related to the variability or dispersion of the hydrogen production estimates around the mean, Piauí displays the highest standard deviation at 829.8 tons/year, indicating a wide range of production estimates and possibly higher uncertainty in its hydrogen production capacity. In contrast, Minas Gerais has the lowest standard deviation at 464.1 tons/year, suggesting more consistent and stable production. Pernambuco and Rio Grande do Norte also show higher variability, which might require further analysis to understand the factors contributing to these fluctuations. This initial analysis highlights the diverse hydrogen production capacities and the associated uncertainties across Brazilian states, offering a comprehensive view of strategic planning and resource allocation.

6.5.2 Stochastic Levelized Cost of Hydrogen (LCOH)

The upcoming analysis investigated the LCOH outputs of the MCS, considering other uncertainties to improve the estimation of variables and potential endogeneities among these stochastically simulated uncertainties. In this way, 10,000 LCOH values were obtained, and then the VaR-LCOH with a confidence level of 95% was calculated, along with the Omega-LCOH, which is particularly suitable for evaluating renewable energy systems at individual locations [87], [188], [222]. Brazilian state's green hydrogen project is represented in Fig. 6.5, showcasing the estimated stochastic LCOH distribution. Compared to single-point estimates (deterministic case), the range of the LCOHs encompasses the inherent uncertainty of investment, presenting a comprehensive approach to assessing the economic feasibility of a project.

Fig 6.5. delves into the stochastic LCOH across the Brazilian state scenarios, evaluating key statistical measures to understand the economic feasibility, stability, and associated risks of different hydrogen production methods. The deterministic values provide a baseline for comparison across different scenarios. LCOH (BA), with a base case of $7.46/kg, emerges as the most cost-effective under standard assumptions, suggesting potential economic advantages. In contrast, LCOH (SP) at $9.99/kg denotes elevated expenditures in typical situations, showing higher costs under typical conditions. This diversity in base case values shows the impact the different conditions and locations can have on the cost of hydrogen production. The mean values offer insight into the overall economic performance. Like the deterministic value, Bahia state has the lowest mean at $6.83/kg, reinforcing its cost-effectiveness and potential as a viable option for low-cost hydrogen production. Conversely, São Paulo has the highest mean at $9.22/kg, suggesting the higher costs to produce hydrogen again, indicating that this state might be less favorable economically.

The base case and mean values of the LCOH provide different perspectives on the cost dynamics associated with various hydrogen production scenarios. The base case represents a single, deterministic estimate under typical conditions, whereas the mean value reflects the average outcome over 10,000 trials, capturing a broader range of potential cost variations.

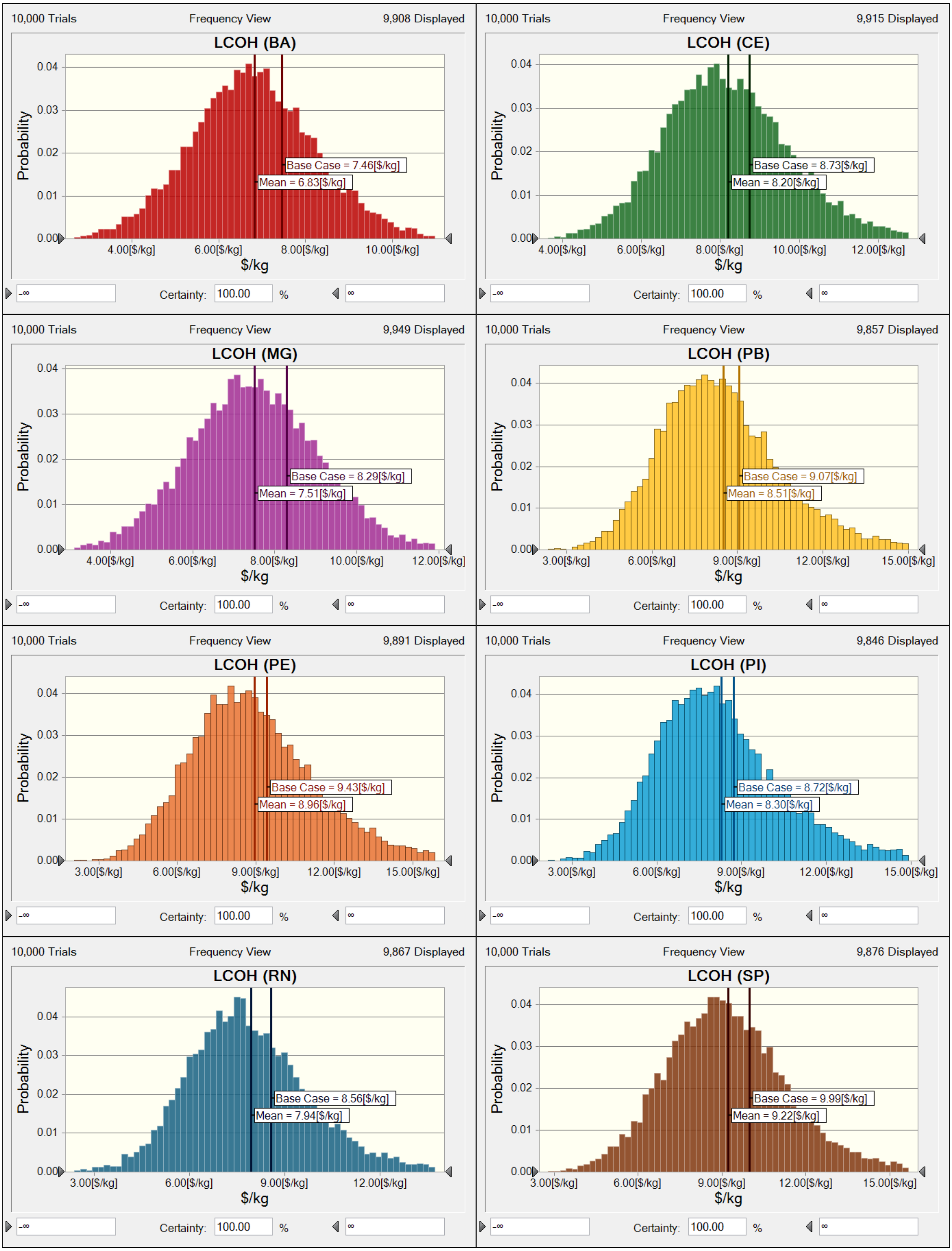


Fig. 6.5. LCOH distribution (based on solar PV hydrogen).

Comparing these distinct approaches across the different scenarios and states provides insights into the expected deviations from typical assumptions and the overall economic feasibility. In most scenarios, the mean LCOH is lower than the base case value, indicating that, on average, hydrogen production costs less than the standard assumption. For instance, the LCOH in Bahia has a base case of $7.46/kg and a mean of $6.83/kg, suggesting that typical costs might be overestimated in the base case. Similarly, Ceará shows a base case of $8.73/kg and a mean of $8.20/kg, and Minas Gerais has a base case of $8.29/kg with a mean of $7.51/kg, both reflecting lower average costs compared to their base cases. This pattern is consistent across all scenarios, with Paraíba, Pernambuco, Piauí, Rio Grande do Norte, and São Paulo all showing mean values lower than their respective base case values. This discrepancy indicates that, while the base case provides a conservative estimate, the actual average costs are generally lower, which could suggest better-than-expected economic performance. However, it also implies that the base case values may encompass potential uncertainties or conservative estimates that are not as prevalent in the actual data. This comparison highlights the importance of considering base case and mean values to comprehensively understand cost expectations in hydrogen production projects.

The LCOH distributions do not differ only in terms of their average estimates and states. Table 6.5 summarizes the main statistics of the LCOH ($/kg) obtained from the stochastic analysis, offering a basis for more in-depth analysis. By comparing these metrics, a more comprehensive understanding of the economic feasibility, stability, and risk associated with each hydrogen production scenario can be achieved.

TABLE 6.5. MCS STATISTICS FOR THE LCOH.

Statistics	**BA**	**CE**	**MG**	**PB**	**PE**	**PI**	**RN**	**SP**
Median	6.77	8.09	7.48	8.23	8.69	7.98	7.72	9.04
Std. Dev.	1.48	1.63	1.57	2.32	2.46	2.36	2.07	2.30
Variance	2.20	2.65	2.45	5.36	6.04	5.57	4.28	5.29
Minimum	1.99	2.98	2.54	2.36	2.00	2.15	2.37	2.53
Maximum	16.61	16.11	15.49	29.36	21.90	21.77	24.52	28.32
Range Width	14.62	13.13	12.95	27.00	19.90	19.62	22.14	25.79
Mean Std. Error	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Skewness	0.3928	0.4140	0.1337	1.15	0.6616	0.9532	0.9662	0.7531
Kurtosis	4.05	3.50	3.10	6.75	3.81	4.72	5.85	5.04
Coeff. of Variation	0.2172	0.1985	0.2085	0.2721	0.2745	0.2845	0.2603	0.2493

The median values represent the midpoint of the LCOH distribution, further confirming the trends observed in the mean values. To illustrate, the median LCOH in Bahia is $6.77/kg, and the median LCOH in São Paulo is $9.04/kg, indicating that Bahia state maintains lower costs, while São Paulo tends to be comparatively more expensive. Since the medians are close to the means most times, it suggests relatively symmetric distributions, but further analyses will be discussed later to confirm or not the normality of the distributions. This proximity between mean and median values indicates that extreme values do not disproportionately influence the average cost estimates.

Under the standard deviation perspective, Bahia has the lowest standard deviation at \$1.48/kg, indicating more predictability and less fluctuation in costs, and Pernambuco has the highest standard deviation at \$2.46/kg, suggesting greater variability and uncertainty in the cost estimates. It is known that the standard deviation is a crucial measure of the volatility and risk associated with investments across different scenarios. Higher standard deviations indicate greater cost variability, suggesting higher uncertainty and risk for investors, while lower standard deviations point to more stable and predictable cost outcomes. Minas Gerais and Ceara have moderate standard deviations, with values reflecting a moderate level of volatility, implying a balanced risk-reward profile for investors. Like Pernambuco, the remaining states also present considerable cost variability, highlighting the potential for substantial deviations from the mean, thus presenting higher investment risks. It is important to note that incorporating financial risk management in TEA for green hydrogen investments extends beyond evaluating standard deviation as a measure of volatility. This encompasses utilizing more robust techniques, such as VaR and Omega, exposed later.

Variance measures the dispersion of cost estimates and further quantifies the cost variability associated with hydrogen production scenarios. The trends in variance are consistent with those of the standard deviation, with BA exhibiting the lowest variance and PE and PB the highest. As seen in Pernambuco and Paraíba, high variance signifies that costs can fluctuate widely, which is crucial for risk assessment and financial planning. Conversely, lower variance in Bahia indicates less risk and more reliable cost predictions due to the minimal cost variability. All the scenarios presented similar mean standard errors (~\$0.01 to \$0.02/kg), indicating high precision in the average LCOH estimates. This uniform precision across scenarios reinforces the reliability of the mean values reported, suggesting that the average costs are estimated with high accuracy.

Minimum and maximum values illustrate the cost range of each scenario, providing insights into the potential cost extremes investors might face under different scenarios. The minimum LCOH values across scenarios range from \$1.99/kg in BA to \$2.98/kg in CE, showing that, under optimal conditions, hydrogen production costs can be pretty low, especially for BA, suggesting favorable cost conditions in the best-case scenario. On the other hand, the maximum LCOH values vary significantly, with PB peaking at \$29.36/kg and SP at \$28.32/kg, indicating a potential for very high costs under certain conditions. With its lower minimum and less extreme maximum, Bahia appears more stable and predictable, which does not occur with Paraíba and São Paulo scenarios that show a broader range between their minimum and maximum values, indicating higher volatility and greater risk of cost fluctuations. These high maximum values highlight the risk and potential for significant cost spikes in these scenarios. By assessing the range between the minimum and maximum values, it is possible to get insight into the extent of potential LCOH outcomes. For this situation, MG has the smallest range at $12.95/kg with more consistent costs, while PB has the widest range at $27.00/kg, indicating greater uncertainty and variability in production costs.

To examine the skewness and kurtosis (Table 6.5) between the scenarios at each state, Fig. 6.6 exhibits an overlay chart to display the relative properties of those LCOHs on one chart. The frequency data from the LCOHs is combined in one figure to show the similarities and differences that may not be readily clear.

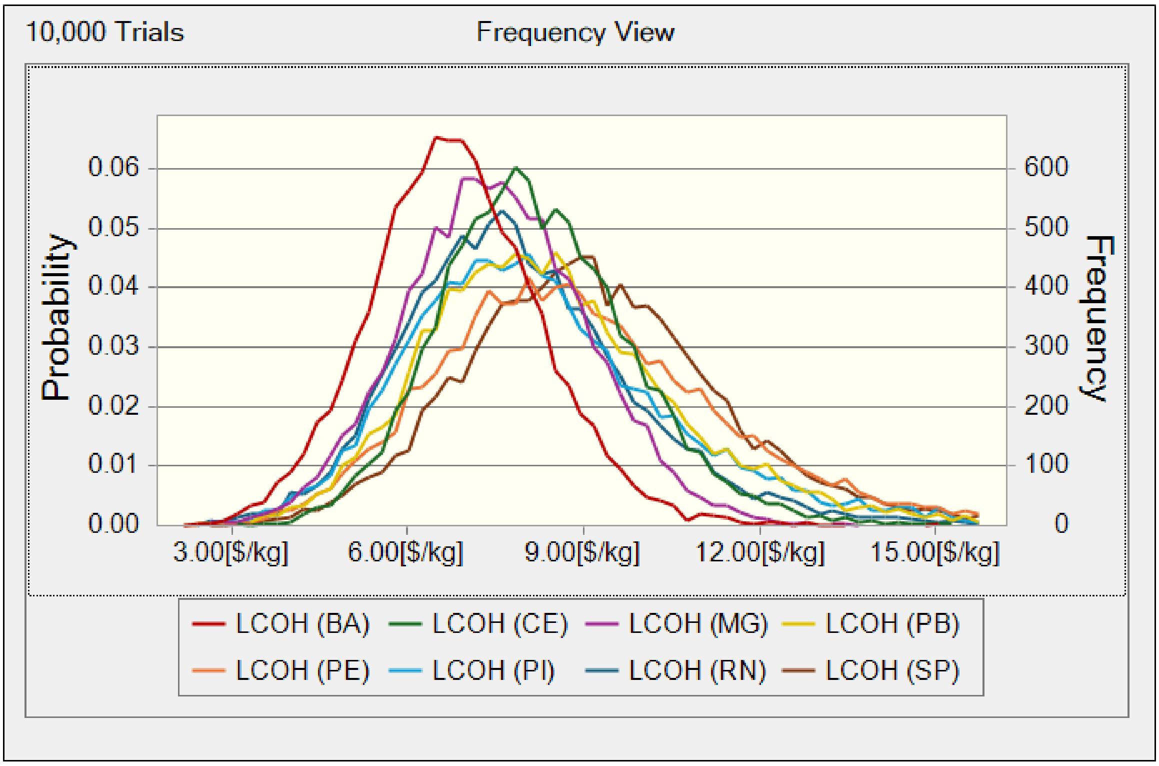


Fig. 6.6. LCOH distribution overlay.

Readers are directed to the article's online version to better understand the color references in this figure legend.

Fig. 5.6 shows the relative reliabilities for the skewness and kurtosis as necessary statistical measures used to understand the distribution characteristics of the LCOH and provide insights into asymmetry and outliers' presence in the LCOH across the states. Positive skewness is seen in all scenarios, suggesting a distribution with a longer right tail, indicating a higher frequency of high-cost outliers. For instance, with the highest skewness of 1.15, PB exhibits a strong positive skew, suggesting that high-cost values are prevalent. In contrast, MG, with the lowest skewness of 0.1337, shows a nearly symmetric distribution, indicating that the costs are more dispersed around the mean, with fewer high-cost outliers.

A case with strong positive skewness (skewness > 1), like PB, indicates a high propensity for large deviations on the higher cost spectrum. Cases such as RN, PI, SP, and PE, which display a moderate positive skew, indicate that, although the cost distribution is symmetrical, there is a propensity for higher outliers. This suggests a moderate probability of encountering costs above the average, but not to an extreme degree, making it relatively stable yet slightly leaning towards higher costs. Scenarios with lower skewness values, such as MG, BA, and CE (skewness < 0.5), present more symmetry and a balanced perspective on cost distributions with a slight positive skewness, indicating a minor tendency towards higher costs but not to an extreme extent. These states offer a good balance of risk and predictability, making them attractive options for reliable hydrogen production cost scenarios.

From the kurtosis point of view, the analysis in PB, RN, PI, and SP exhibit a leptokurtic behavior for the distributions in these states. For instance, PB has a kurtosis of 6.75, the highest among the Brazilian states, indicating a significant risk of facing high costs. Similarly, RN and PI have high kurtosis values, respectably 5.85 and 4.72, signaling that these three states are more prone to outliers, elevating the unpredictability in the cost estimation. Oppositionally, the LCOH distribution in MG has the lowest kurtosis at 3.10, with fewer extreme values and a more predictable cost structure, approximating this distribution to a normal distribution (mesokurtic) with moderate tail thickness. This mesokurtic characteristic balances moderate variability and stability, demonstrating that extreme cost deviations are less probable than leptokurtic distributions.

6.5.3 Sensitivity analysis findings

In order to investigate the impact of the techno-economic, physical, and financial assumptions (see Table 5.4) on the cost of hydrogen production and to uncover potential reductions in hydrogen costs both currently and in the future, a sensitivity analysis was conducted on LCOH for the different Brazilian states approached in this case study. The sensitivity analysis can provide valuable insights into the impact of the assumptions on the final cost estimate. The correlations derived from the Monte Carlo simulations indicate which factors are most critical in influencing LCOH, thereby guiding future efforts to optimize hydrogen production and reduce costs. The results are presented in Fig. 6.7.

Regarding financial factors, both inflation and exchange rate have the expected desirable inverse relationship with the LCOH, and a more in-depth explanation is necessary to contextualize the inflation effects in the LCOH. As shown in Fig. 6.7, the inflation rate consistently indicates the highest negative correlation with LCOH across all states, ranging from -29.9% in Pernambuco to -46.5% in Minas Gerais. Minas Gerais's LCOH is highly sensitive to changes in the inflation rate, suggesting a firm reliance on effective financial management. Bahia and São Paulo have significant negative correlations, showing the importance of stable economic conditions and favorable financing terms in effectively managing the inflation in these regions to reduce the LCOH. Pernambuco and Piauí present a less pronounced effect of inflation than MG, BA, and SP but still significantly impact LCOH.

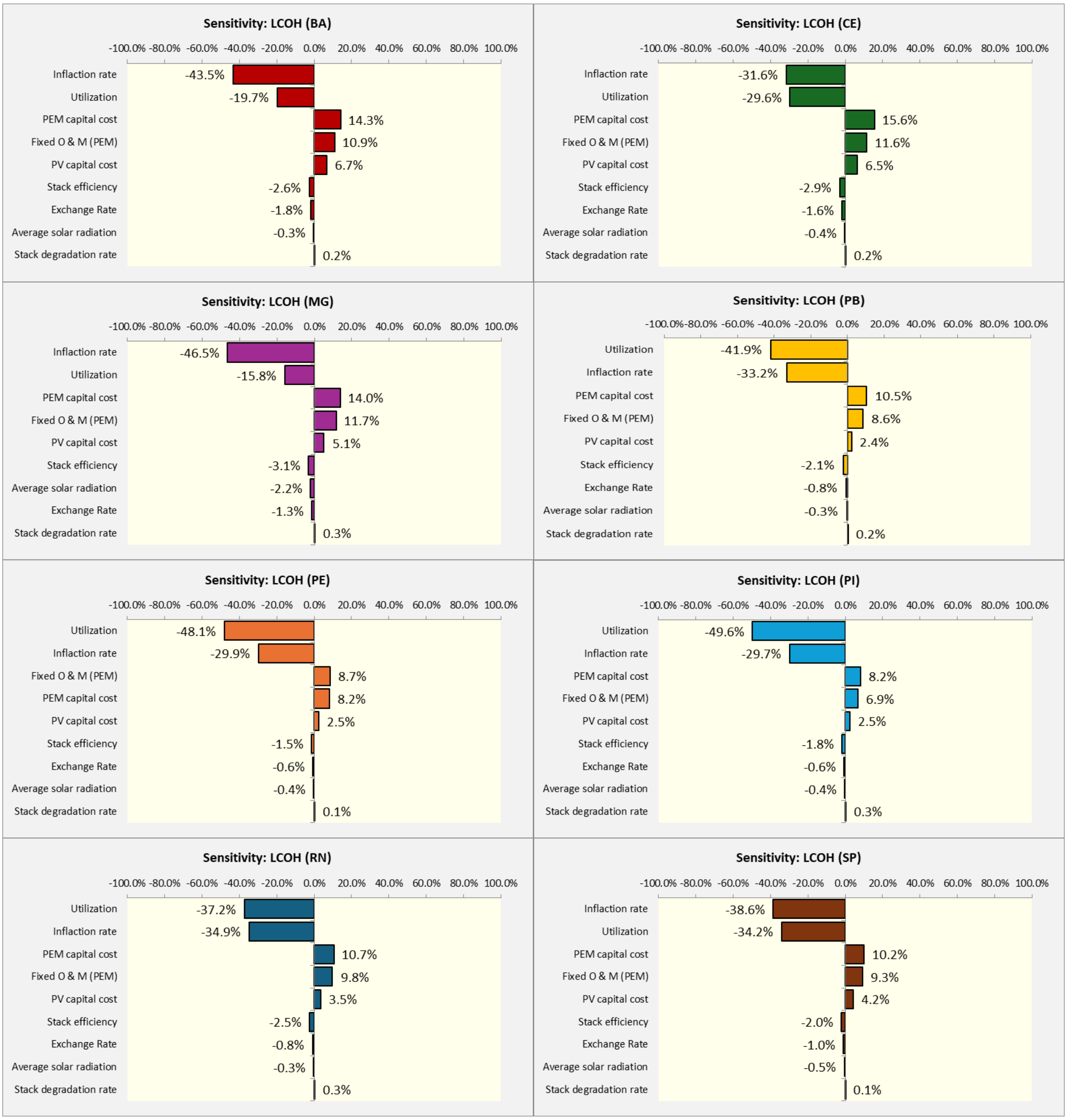


Fig. 6.7. Key cost drivers to LCOH.

The inflation rate's strong negative correlation with LCOH across Brazilian states highlights its critical role in hydrogen production cost analysis. This strong negative correlation suggests that as inflation rates increase, the LCOH significantly decreases. This outcome might seem arbitrary initially, but it likely reflects the inflation rate’s impact on discounting future costs. The decrease in LCOH with higher inflation rates occurs because the present value of future costs (OpEx and RepEx) decreases when the inflation rate discounts the WACC, which is subsequently used to equate the present value of the lifetime costs with the present value of the lifetime hydrogen generation (refer to Eq. 6.2).

Managing inflation and understanding its trajectory becomes critical for long-term financial planning and investment in hydrogen production infrastructure. Implementing robust financial management strategies, including inflation hedging and the acquisition of favorable financing terms, is crucial for mitigating the negative impact of inflation on WACC and, by extension, on LCOH. Given the variability in inflation sensitivity across states, region-specific financial strategies are crucial for optimizing hydrogen production costs and enhancing economic feasibility. The PDF attributed to all the states is based on data for the IPCA for the whole country, but it is known that the inflation rate can vary from one state to another. This factor should be considered in future research to predict better the LCOH's behavior regarding these regional financial issues.

A direct correlation exists between the inflation rate and the capital and debit cost, operational cost, and supplies cost [270], [271], [272]. If inflation rises, lenders may demand higher interest rates to compensate for losing the purchasing power of the money borrowed, thus increasing the cost of debt. Likewise, equity investors may demand higher nominal returns to maintain their purchasing power, increasing the cost of equity [271], [273]. Increased component costs often accompany higher inflation rates. Simultaneously, the prices of raw materials, labor, and other necessary resources for manufacturing these components rise, leading to this outcome [265]. This could lead to an increase in the project's overall life cycle operating costs. Although extremely important, these aspects relating to the impacts of inflation on the LCOH calculation were not taken as a hypothesis in this study.

The exchange rate is a financial assumption that influences the LCOH and impacts the cost of imported equipment, materials, and services necessary for hydrogen production. Variations in the exchange rate can lead to fluctuations in these costs, affecting the overall economic feasibility of hydrogen projects [274], [275]. The correlations between the exchange rate and LCOH are relatively low, ranging from -0.5% in PB to -2.2% in MG, indicating that while the exchange rate does impact LCOH, its direct influence is less significant compared to other factors, like the inflation rate. States with higher negative correlations (e.g., MG, BA, CE) should mitigate exchange rate risks by diversifying supply chains, securing long-term contracts in local currency, or using financial instruments like hedging [276]. By adopting strategic financial practices and increasing local sourcing, states can better control production costs and enhance the sustainability of their hydrogen industry.

The utilization rate of the electrolyzer, which is influenced by the PV capacity factor, directly impacts hydrogen production efficiency and costs. The PV capacity factor represents the ratio of electricity produced by the PV system to the maximum electricity it could produce under ideal conditions. Given that the utilization rate is inherently linked to the availability and efficiency of solar energy, this discussion examines how the PV capacity factor affects the correlation between utilization and the LCOH across the Brazilian states. The correlation between utilization and LCOH for each state reveals a significant negative impact, with correlations ranging from -15.8% in MG to -49.6% in PI. Particularly in PE, RN, and PI, where utilization shows the highest negative correlations, ensuring high operational uptime of electrolyzers is paramount (i.e., more consistent and efficient operation influenced by the PV capacity factor) to reduce the LCOH.

The type of PDF used (Normal or Weibull) provides insights into the expected variability and reliability of operational performance in each state. States with higher variability in utilization (modeled by the Weibull distribution) may need to focus on stabilizing their operations to achieve cost reductions. States with utilization modeled by a normal distribution should aim to maintain and slightly improve their operational efficiency to benefit from lower hydrogen production costs. Understanding the influence of the PV capacity factor on utilization helps optimize the operational strategies to achieve cost-effective hydrogen production.

Solar radiation is a physical assumption that influences LCOH by impacting the efficiency and capacity factor of PV systems. In theory, higher solar radiation leads to a higher capacity factor, which increases the utilization rate of electrolyzers, enhancing hydrogen production efficiency and reducing LCOH. However, high solar radiation does not always translate directly to a high-capacity factor. This nuanced relationship is apparent in the PB state, which has high solar PV irradiance (6.09 kWh/m2) but a relatively low-capacity factor (21.66%) compared to other states for the deterministic perspective, which highlights that the operational efficiency is more critical than solar radiation alone in reducing LCOH. This discussion is based on the data provided by NASA for solar radiation, the Brazilian National Electric System Operator, and the finding of this study (see Fig. 6.8), showing that a high PV potential does not always lead to a high capacity factor, which in practice is might be affected by factors such system design and installation, operational and maintenance practices and environmental conditions [277].

Fig.5.8 underscores the critical role of utilization rates in reducing the LCOH across Brazilian states. While average solar radiation provides a necessary foundation for energy production, its direct impact on LCOH is limited. The weak correlations between average solar radiation and LCOH (ranging from -0.3% to -1.3%) suggest that, while solar radiation provides energy for PV systems, its direct impact on reducing LCOH is minimal. Maximizing utilization through efficient system management, maintenance, and operational strategies is key to achieving cost-effective hydrogen production. States with high solar potential must optimize these additional factors to leverage their solar resources and reduce LCOH entirely.

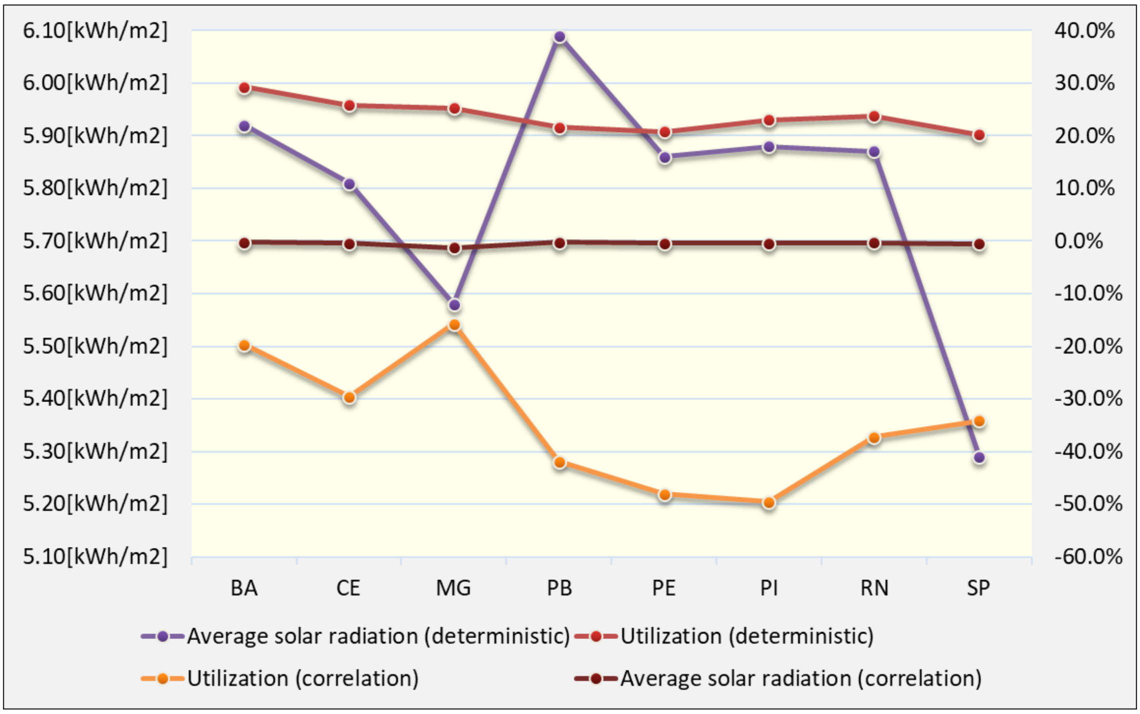


Fig. 6.8. Physical assumptions influencing LCOH.

The PEM and PV Capital costs, modeled using a Beta PERT distribution, correlate positively with LCOH across all states. For PEM capital cost, correlations vary from 8.2% in PE and PI to 15.6% in CE, while for PV capital cost, from 2.4% in PB to 6.7% in BA. Elevated initial investments in PEM electrolyzer systems increase the LCOH, underlining the importance of cost-effective procurement and installation of PEM systems. The relatively higher impact in CE and BA indicates that controlling capital expenditures is decisive in these states to maintain competitive LCOH levels. PV capital cost correlations are less impactful compared to PEM capital costs, and they are directly related to utilization assumptions since the size of the PV system is dimensioned according to the local solar PV capacity factor. Technological improvements and competitive pricing in the PV market could still contribute to overall cost reduction. The fixed O&M costs for PEM systems also positively correlate with LCOH, with correlations ranging from 6.9% in PI to 11.7% in MG, underscoring the importance of managing ongoing operational expenses to maintain economic feasibility. States like MG and CE (11.6%) should optimize O&M practices to minimize their impact on LCOH.

Stack efficiency and degradation rate maintain weak correlations with LCOH. Stack efficiency correlations are negative, ranging from -1.5% in PE to -3.1% in MG, suggesting that enhancements in efficiency slightly reduce LCOH. The degradation rate correlations are close to zero (0.1% to 0.3%), indicating minimal impact. Although the technical parameters mentioned may not be the main factors affecting the LCOH, it is crucial to focus on enhancing stack efficiency and effectively managing degradation in order to create a hydrogen production system that is both reliable and economically viable.

The analysis reveals regional differences in the sensitivity of LCOH to various factors. For instance, BA, CE, MG, and SP are highly sensitive to inflation rates, indicating the importance of economic policies in these regions. PB, PE, PI, and RN show significant sensitivity to utilization rates, highlighting the need for robust operational strategies. CE and BA exhibit sensitivity to PEM capital costs, suggesting a focus on reducing initial investment costs. The comprehensive analysis indicates that financial factors, particularly inflation and utilization rates, are the most influential determinants of LCOH. While technical improvements and cost management in PEM and PV systems are important, broader economic conditions and operational efficiencies play a crucial role in driving cost reductions. This multifaceted approach will be vital to achieving sustainable and competitive hydrogen production across different regions in Brazil.

6.5.4 VaR-LCOH stochastic approach

After the stochastic approach, the first step was to estimate the VaR-LCOE through the LCOH values for each state based on uncertainties modeled by assumptions in Table 5.4. This way, the VaR-LCOE was calculated with a 95% confidence level. Fig. 6.9 encompasses the VaR-LCOH for the analyzed states presented graphically by the MCS.

Fig. 6.9 displays the Value at Risk (VaR) at a 95% confidence level for the Levelized Cost of Hydrogen (LCOH) across the Brazilian states. The VaR-LCOH represents the maximum expected cost of hydrogen production under adverse conditions, indicating the potential financial risk and variability. Each subplot provides a frequency view of the LCOH distribution, fitted with a log-normal curve, and highlights the certainty max (VaR-LCOH) value. The certainty max value is the threshold below which the LCOH is expected to remain with 95% confidence.

The VaR-LCOH values range from \$9.30/kg in Bahia (BA) to \$13.44/kg in Pernambuco (PE), representing a \$4.14/kg range. This wide range underscores the varying risk and cost predictability levels across the states. Pernambuco exhibits the highest VaR-LCOH at \$13.44/kg, a substantial increase from its base case value of \$9.43/kg, reflecting a 42.5% rise. This significant difference indicates a high potential for cost escalation under adverse conditions, suggesting considerable variability and financial risk. The high VaR-LCOH value in Pernambuco implies that hydrogen production costs could become quite expensive and unpredictable, imposing deep financial planning and risk mitigation strategies to manage potential cost spikes effectively.

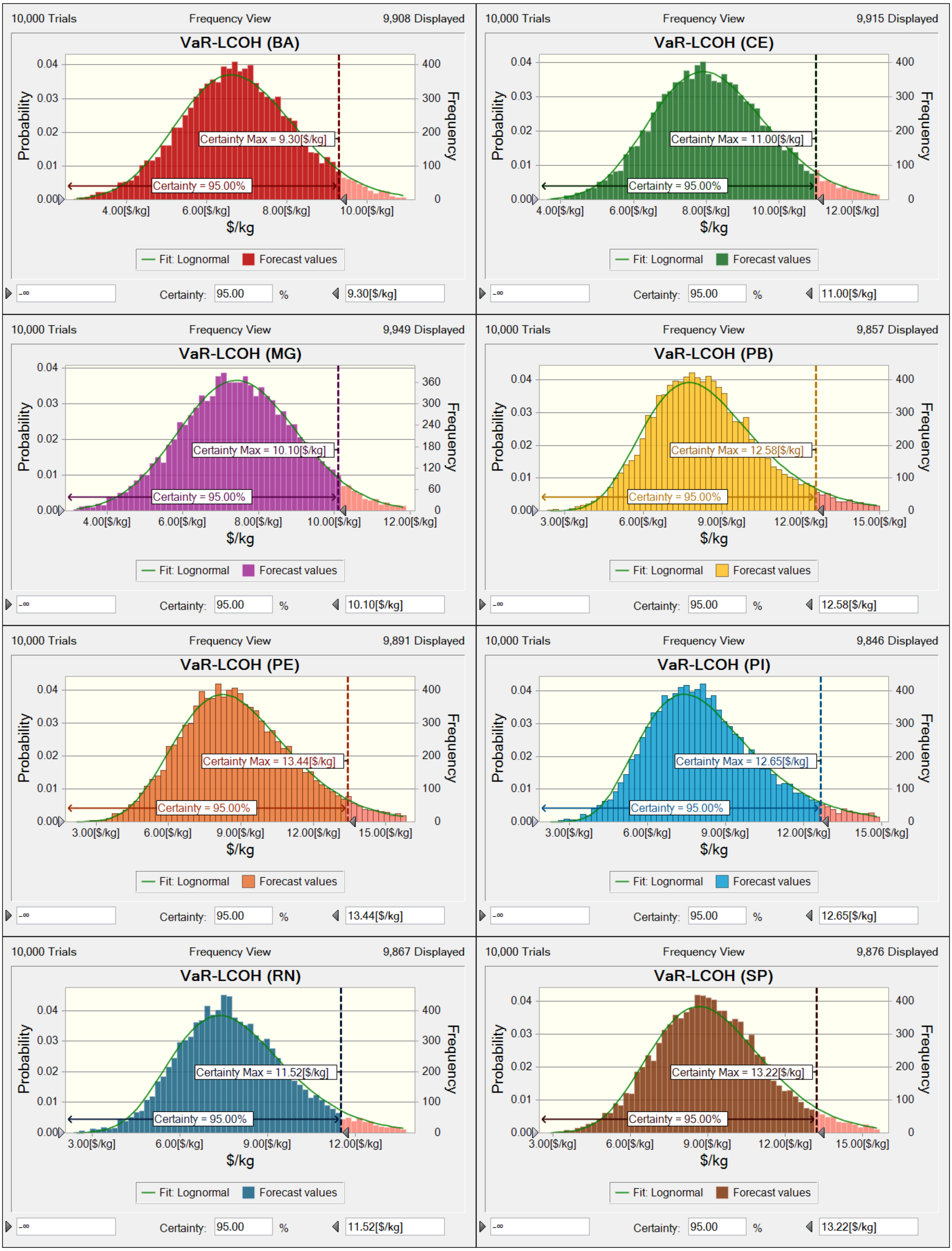


Fig. 6.9. VaR-LCOH estimation in Brazilian states.

Similarly, São Paulo has a high VaR-LCOH at \$13.22/kg, up from a base case of \$9.99/kg, representing a 32.3% increase. This indicates significant risk and cost variability, suggesting that hydrogen production in São Paulo could face substantial financial uncertainty. Paraíba (PB) and Piauí (PI) also show high VaR-LCOH values at \$12.58/kg and \$12.65/kg, respectively, with increases of 38.7% and 45.1% (highest increase) from their base cases. These substantial increases highlight the need for robust financial strategies and risk management in these states to cope with potentially high production costs.

Rio Grande do Norte and Ceará exhibit moderate VaR-LCOH values of \$11.52/kg and \$11.00/kg, respectively. The increases from their base cases—34.6% for RN and 26.0% for CE—reflect moderate risk profiles. These states show balanced cost variability, requiring prudent financial strategies to ensure economic viability while managing potential cost fluctuations. Minas Gerais and Bahia have the lowest VaR-LCOH values, with MG at \$10.10/kg and BA at \$9.30/kg. Minas Gerais shows a 21.8% increase from its base case of \$8.29/kg, while Bahia exhibits a 24.7% rise from \$7.46/kg. These relatively low increases indicate much greater cost stability and predictability. The stable cost conditions in these states make them attractive options for risk-averse investors seeking more consistent and predictable cost outcomes in hydrogen production.

Comparing the states, Pernambuco, São Paulo, Paraíba, and Piauí present the highest potential costs and significant variability, categorized as high-risk states, imposing robust financial strategies and risk management practices. Rio Grande do Norte and Ceará shows moderate risk profiles with balanced cost variability, while Minas Gerais and Bahia stand out for their stable and predictable cost environments (low-risk states). Bahia, in particular, offers the lowest VaR-LCOH, making it the most favorable option for risk-averse investors due to its lower potential for extreme cost increases.

The Brazilian states' fitted probability distributions (log-normal curve) revealed significant differences in cost risk profiles and were used to estimate the VaR-LCOH. States with highly skewed distributions, like PE and SP, face more significant financial uncertainty and the potential for extreme cost outcomes. In contrast, states with more symmetrical distributions, like MG and BA, offer more stable and predictable investment environments. The lognormal distribution is widely used in several fields to model positively skewed data where most values occur near the minimum value) and where values cannot fall below zero, like in financial analysis for security valuation or in real estate for property valuation [278]. The lognormal distribution is well-suited to describing the behavior of levelized costs due to its ability to handle skewed, non-negative data and capture the multiplicative nature of cost influences, making it a valuable tool for predicting and managing financial risks in the hydrogen production industry [279], [280].

The VaR-LCOH analysis highlights the diverse risk profiles and cost variability associated with hydrogen production across Brazilian states. Understanding these differences is essential for stakeholders to make informed decisions and develop effective strategies for managing financial risks. This comprehensive understanding helps guide strategic planning and investment decisions in the hydrogen production sector.

6.5.5 Omega-LCOH stochastic approach

In this context, the Omega ratio provides a nuanced view of the risk-return profile of a cost distribution, such as the LCOH. The Omega-LCOH stochastic approach involved the initial performance of 10,000 Monte Carlo simulation iterations to calculate the LCOH. The uncertainties were inserted from the distributions with parameters provided in Table 6.4 for each Brazilian state. Table 6.6 describes the LCOH percentage below the threshold value ($6.00/kg [281]) and the respective results obtained for each state.

TABLE 6.6. OMEGA-LCOH RESULTS.

States	**LCOH average > Benchmarking**	**I_2**	**I_1**	**Omega-LCOH**
BA	113.8%	0.29	0.71	0.41
CE	136.7%	0.08	0.92	0.08
MG	125.2%	0.17	0.83	0.20
PB	141.8%	0.11	0.89	0.12
PE	149.3%	0.91	0.09	0.10
PI	138.3%	0.14	0.86	0.16
RN	132.3%	0.15	0.85	0.18
SP	153.7%	0.06	0.94	0.06

The Omega ratio is the ratio of the probability-weighted gains (returns above a threshold) to the probability-weighted losses (returns below a threshold). An Omega above 1 indicates that the probability of achieving outcomes better than the threshold is greater than the probability of achieving outcomes worse than the threshold, while a value less than 1 indicates the opposite. Specifically, an Omega-LCOH above 1 suggests that the difference between the average LCOH values below $6.00/kg (I2) is more significant than the potential for loss or an average of the difference between LCOH values above $6.00/kg, referencing the benchmark for this analysis (I1). This insight is depicted in Fig 6.10 using the threshold ($6.00/kg) and the gains and losses for each state.

The Omega-LCOH, which compares the probability of outcomes being above or below a specified threshold, is pivotal in understanding hydrogen production costs' efficiency and risk profile across different states. For the data, Omega-LCOH values are significantly below one across all states, indicating predominant chances that costs will be above the $6.00/kg threshold. This consistent pattern suggests that the varying averages of LCOH exceed the benchmark, and the probability distribution indicates higher costs, pointing to an unfavorable cost environment.

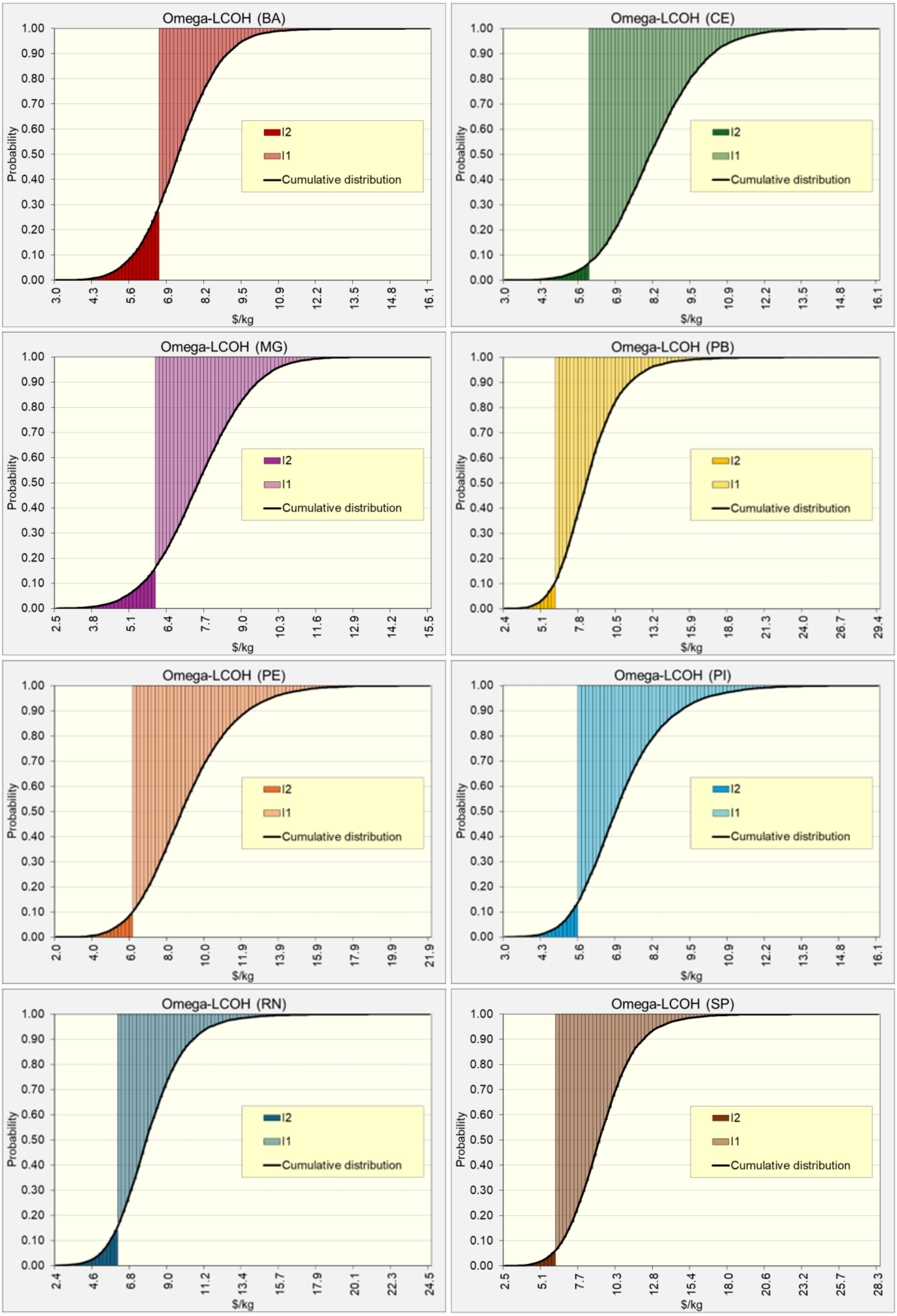


Fig. 6.10. Components of the Omega ratio.

First, the LCOH average indicates how much the average cost of hydrogen production exceeds the \$6.00/kg benchmark. For instance, BA has an LCOH average of 13.8% higher than the benchmark, with a 29% probability that costs are below the threshold and a 71% probability that costs exceed \$6.00/kg. This indicates that the probability of incurring losses is more than twice that of achieving gains. Specifically, for every unit probability of gains, there is a 2.45 times greater probability of losses, showing that the state's cost management practices are not sufficiently compelling to maintain costs below the threshold frequently enough.

Ceará has one of the lowest Omega-LCOH. The Omega value of 0.08 signifies extreme inefficiency, with the probability of losses being 12.5 times greater than the probability of gains. With an LCOH average of 36.7% higher than the benchmarking, it is clear that costs are frequently above the threshold, reflecting severe inefficiencies in managing production costs. The meager Omega value highlights the need for substantial improvements in cost control. In Minas Gerais, the Omega-LCOH (0.20) also indicates significant inefficiency with the probability of incurring losses five times greater than achieving gains. Given the LCOH average of 25.2%, this state needs to enhance its cost management strategies to reduce the frequency of higher costs.

Paraíba, with its low Omega-LCOH, only 0.12, indicates that the probability of losses is 8.3 times greater than the probability of gains. The LCOH average of 41.8% reflects substantial inefficiency, as costs are frequently above the threshold. In Pernambuco, the Omega-LCOH of 0.10 highlights a high level of inefficiency, with the probability of losses being nine times greater than the probability of gains. Despite a high I2 value of 0.91, the LCOH average of 49.3% suggests that frequent high costs dominate, pointing to critical inefficiencies that require significant improvements in cost management. Piauí has an Omega-LCOH value of 0.16, indicating inefficiency, with the probability of losses being 6.25 times greater than the probability of gains. The LCOH average of 38.3% reflects that while some controlled costs exist, high-cost instances are widespread.

Rio Grande do Norte, with an Omega-LCOH value of 0.18, also shows inefficiency, and the probability of incurring losses is 5.56 times greater than achieving gains. The LCOH average of 32.3% higher than the benchmarking indicates that while some costs are managed effectively, the overall frequency of higher costs needs to be reduced. For São Paulo, the Omega-LCOH value is 0.06, the lowest compared with the other states, indicating extreme inefficiency. The probability of losses is 16.67 times greater than the probability of gains, having the highest LCOH average at 53.7% compared to the benchmarking. This light Omega value highlights the significant need for targeted interventions to address high-cost instances and improve cost efficiency.

An Omega value below one unequivocally indicates inefficiency, where the probability of losses (costs above the threshold) outweighs the probability of gains (costs below the threshold). States like CE, SP, PE, and PB exhibit extreme inefficiency, suggesting significant improvements in cost management. While still inefficient, other states like BA, MG, PI, and RN show fewer extreme disparities between the probabilities of losses and gains, indicating areas where focused cost control efforts could improve efficiency. Understanding these inefficiencies can contribute to developing strategies to reduce hydrogen production costs and effectively mitigate associated risks.

The Omega-LCOH values below across the Brazilian states directly result from the limit imposed by the benchmarking, reflecting a highly realistic scenario in the country. Given the current technological and economic conditions, this constraint underscores the prevalent challenges in achieving low-cost hydrogen production. The industry faces real-world constraints impacting hydrogen investment's overall efficiency and cost structure, increasing the LCOH. These constraints are driven by several key factors, and in this study, especially by the PEM capital cost and the utilization rate, which is directly linked to the local PV capacity factor, mainly when PV is the sole source of electricity.

The high initial investment required for the whole PEM system increases the baseline cost of hydrogen production. This is especially pronounced in regions where the economic conditions may not favor such high upfront expenditures, leading to a higher average LCOH. Furthermore, the utilization rate, attached to the PV capacity factor, heavily influences the operational efficiency of hydrogen production facilities. The PV capacity factor varies significantly across regions due to geographical and climatic conditions. In regions with lower PV capacity factors, the utilization rate of the electrolysis systems is reduced, leading to underutilization of the PEM infrastructure. This underutilization increases per-unit production costs since the fixed capital costs are spread over less produced hydrogen. These challenges impose limits and make the industry's need to navigate these constraints effectively.

6.6 Generalized outlook for the LCOH

Hydrogen production across Brazilian states shows significant variability due to differences in solar PV capacity factor and solar radiation. Bahia has the highest hydrogen production capacity, while São Paulo has the lowest. Variability is high in states like Piauí, which indicates more significant uncertainty in hydrogen production estimates. The stochastic analysis of LCOH reveals significant variability and economic feasibility differences across Brazilian states. Bahia emerges as the most cost-effective region, with a mean LCOH of \$6.83/kg, while São Paulo shows the highest mean LCOH of \$9.22/kg. This analysis highlights the economic advantages of hydrogen production in regions with favorable conditions, like Bahia. The base case and mean values, alongside statistical measures such as standard deviation and variance, provide a comprehensive understanding of cost dynamics. States with higher variability, such as Pernambuco and Paraíba, indicate greater investment risks, requiring robust financial strategies to manage potential cost fluctuations. This diverse cost landscape underscores the need to design financial and operational strategies to enhance the economic viability of hydrogen production projects across different states.

The sensitivity analysis identifies key factors influencing LCOH, with electrolyzers' inflation and utilization rates being the most significant. States like Minas Gerais and São Paulo, highly sensitive to inflation rates, emphasize the importance of effective financial management to stabilize costs. High utilization rates in states like Pernambuco and Piauí highlight the need for operational efficiency to reduce costs. The analysis also indicates that although impactful, PEM capital and PV capital costs have a relatively lower influence than financial factors. This multifaceted approach to understanding cost drivers informs strategic decisions to optimize hydrogen production costs, emphasizing the critical role of economic policies and operational efficiencies.

The VaR-LCOH analysis at a 95% confidence level provides insights into the potential financial risks associated with hydrogen production. States like Pernambuco and São Paulo exhibit the highest VaR-LCOH values, indicating significant cost variability and financial uncertainty. Conversely, with lower VaR-LCOH values, Bahia and Minas Gerais present more stable and predictable cost environments, making them attractive to risk-averse investors. Fig 6.11 presents a graph with the percentiles of the LCOH that also can exhibit a comprehensive view of VaR.

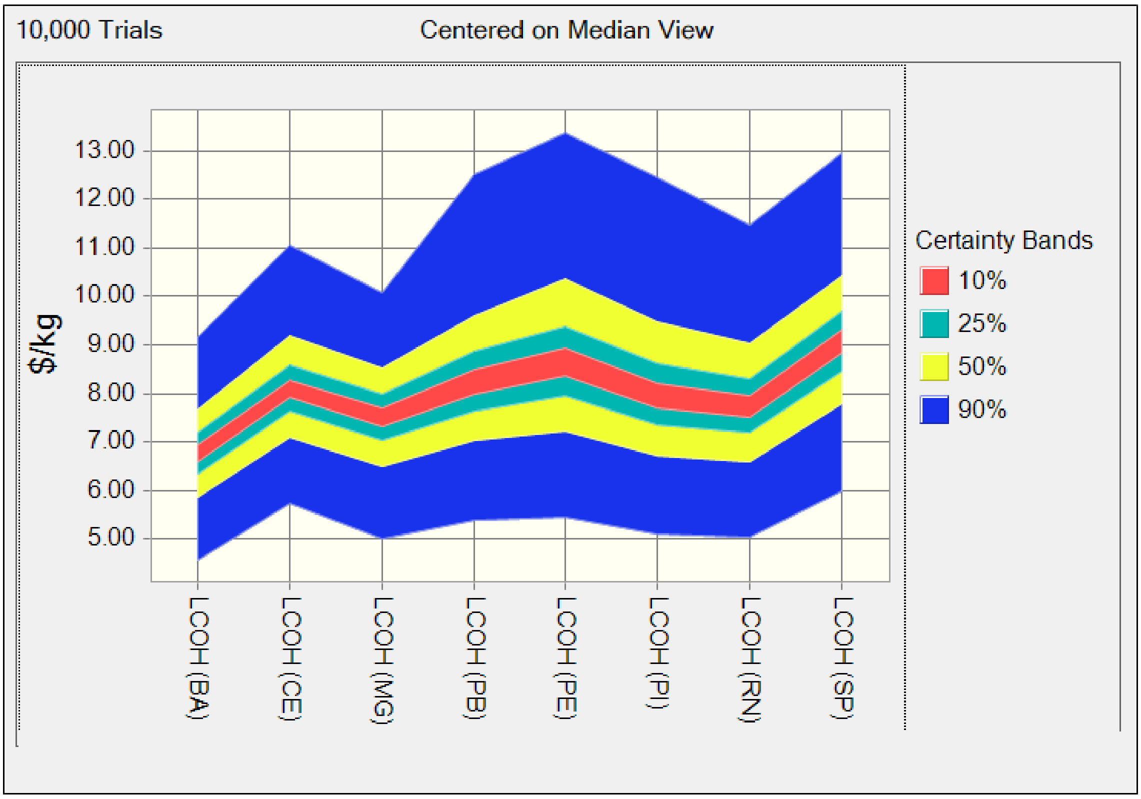


Fig. 6.11. Certainty bands for LCOH.

Fig 5.11 provided a band chart illustrating the cost per kilogram ($/kg) for different states centered on the median view. These bands help to understand the range and confidence of cost estimates across different states, each denoted by their abbreviations. The 10% band is the narrowest, indicating the highest confidence with the slightest variation, while the 90% band is the widest, reflecting the most considerable uncertainty in the cost estimates. The certainty bands directly correlate with the concept of VaR, which measures the potential loss in value of an investment over a specified period for a confidence interval. Higher certainty bands, particularly the 90% band (blue), correlate with higher VaR, indicating significant potential cost and risk variations.

Conversely, lower certainty bands, such as the 10% (red), correlate with lower VaR, as the minimal cost variation indicates minor risk. The certainty band chart visualizes potential cost variations and associated risks across states. States with broader bands, especially the 90% band, like LCOH (RN) and LCOH (SP), indicate higher uncertainty and thus higher VaR, and states with narrower bands, such as LCOH (CE) and LCOH (PI), demonstrate more stable costs and lower VaR.

Comparing the VaR-LCOH approach to the deterministic approach in investment decision-making reveals crucial insights. The VaR-LCOH approach ranks higher in cost because it incorporates a comprehensive risk assessment, and while this results in higher cost estimates, it is essential to understand and prepare for worst-case scenarios. This risk-inclusive approach provides a more realistic and conservative estimate, which is helpful for long-term planning and investment, as shown in Fig 6.12.

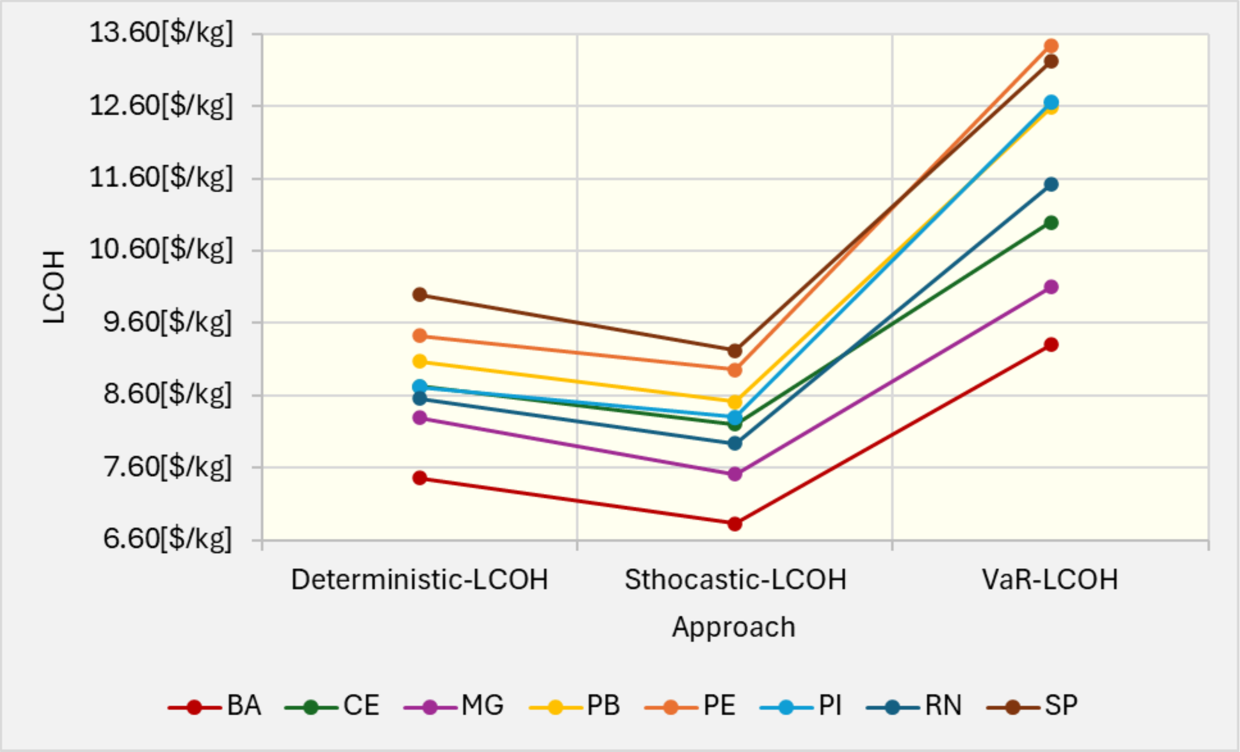


Fig. 6.12. LCOH values by approach.

Interestingly, Fig. 6.12 shows that the worst-case LCOH values under the VaR approach in some categories, such as BA, are lower than the LCOH values for other categories, such as SP and PE, under the deterministic approach. Also, the worst scenario in MG for the VaR-LCOH presents a value slightly above the deterministic LCOH in SP. This highlights that even with conservative risk assessments, certain states can manage costs more effectively under adverse conditions than others operating under normal conditions with a deterministic method. This comparison underscores the importance of adopting a risk-aware strategy in hydrogen investment.

For financial risk management, relying only on deterministic estimates might underestimate potential costs and lead to unpreparedness for adverse scenarios. The VaR-LCOH approach, despite its higher cost projections, provides an approach against uncertainties and better prepares investors for potential financial impacts. Therefore, encompassing risk assessments into cost estimations provides a safeguard and shows areas where cost control can be optimized even under critical conditions, making the approach a robust and reliable method for planning and investment in hydrogen.

In the evolving field of hydrogen production, evaluating the LCOH requires a multifaceted approach, incorporating different financial risk management strategies to capture the full spectrum of uncertainties. Considering different approaches, such as VaR-LCOH and Omega-LCOH, allows for a comprehensive analysis that accounts for predictable factors and potential fluctuations in cost and performance. These methodologies provide a nuanced understanding of the cost dynamics and the next level for stochastic analysis, ensuring that decision-makers can select the most resilient and cost-effective options for the investment. For a detailed analysis and a visual representation of how these approaches impact state rankings regarding LCOH, please refer to Fig. 6.13, where the Omega ratio approach is coupled to this study, explaining the efficiency and risk profile of hydrogen production costs.

Fig. 6.13 examines the LCOH across different states using different approaches, including Deterministic-LCOH, Stochastic-LCOH, volatility of the stochastic analysis as a measure of the standard deviation over a specific time horizon, VaR-LCOH, and Omega-LCOH. Each method provides a distinct perspective on evaluating LCOH by accounting for different factors and uncertainties, which are essential for making informed investment decisions in hydrogen production. By comparing the rankings of states using these methods, it aims to identify the competitive, cost-effective, and stable options for hydrogen production. The results highlight significant differences in cost-effectiveness depending on the approach used, providing valuable insights into decision-making.

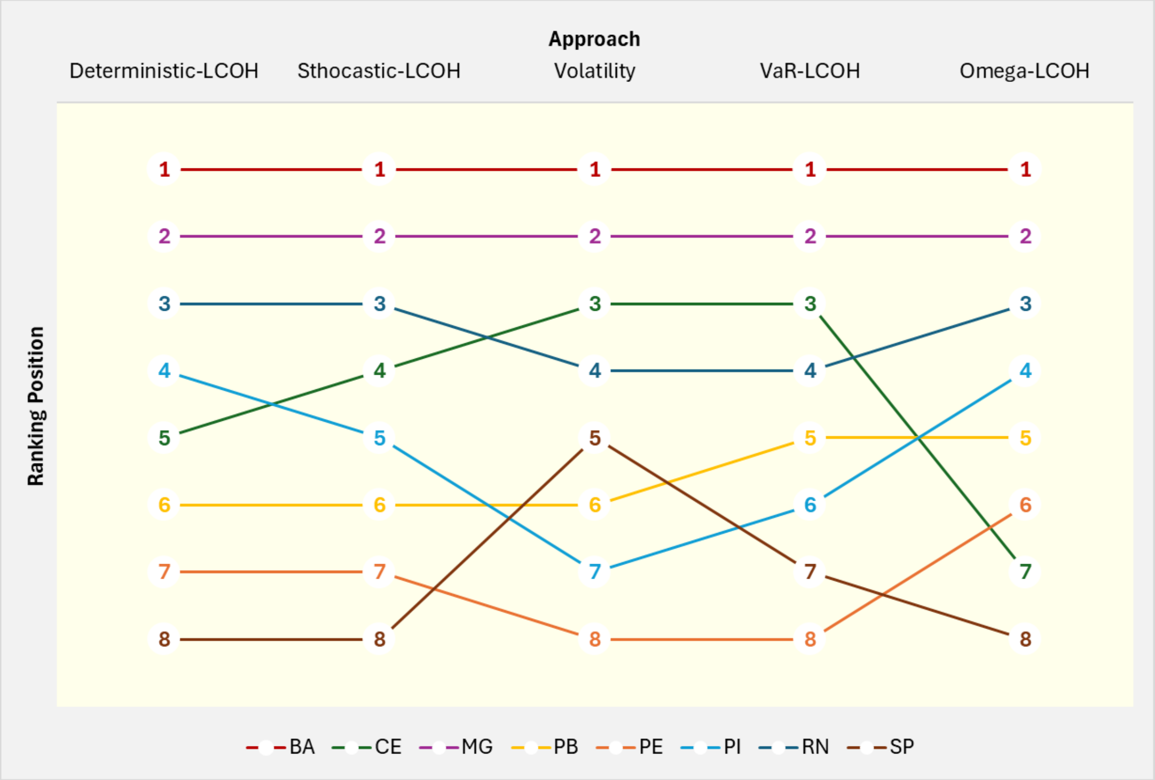


Fig. 6.13. LCOH ranking by approach.

Under the deterministic approach, which considers only fixed input parameters without accounting for uncertainties, variability, or risk, the state of BA consistently ranks first, indicating the highest cost-effectiveness. MG follows closely, ranking second, while RN holds the third position. CE, PI, PB, PE, and SP rank lower, with SP being the least cost-effective. The consistency of BA and MG in maintaining their top positions suggests strong economic efficiency under fixed conditions. The stochastic approach introduces randomness and uncertainty into the cost estimates, reflecting more realistic scenarios. Despite this, BA and MG maintain their first and second positions, respectively, demonstrating their robustness against stochastic variations. RN also maintains its third position, further emphasizing its reliability. CE improves slightly to fourth place, while PI drops to fifth, highlighting its sensitivity to stochastic factors. PB, PE, and SP remain at the bottom, indicating their relative inefficiency under uncertain conditions.

There are notable changes when evaluating volatility, which assesses the impact of cost fluctuations and measures variation in LCOH. CE improves significantly in third place, showing its competitive edge when accounting for fluctuating costs. SP also shows improvement, moving to fifth place, suggesting a better performance in a volatile environment. However, PI and PE drop in rankings, indicating higher sensitivity to volatility and less cost stability under fluctuating conditions. BA and MG remain stable at the top, reaffirming their economic efficiency and resilience.

The VaR approach assesses the potential for extreme losses in the LCOH. Under this metric, BA remains the most cost-effective state, with MG still in second place. PB shows improvement, moving to fifth place, indicating better performance under extreme risk scenarios. PI and CE perform moderately, while PE and SP remain less competitive, highlighting their vulnerability to high-risk conditions. Last, the Omega-LCOH approach, which evaluates performance based on reward-to-risk ratios, reveals significant changes, providing a balanced view of cost-effectiveness. BA and MG continue to dominate the top positions, reinforcing their cost-effectiveness. RN state consistently performed well, maintaining a high ranking. However, CE drops to seventh place, suggesting a poor reward-to-risk ratio. PI improves to fourth place, indicating better relative performance when considering risk-adjusted returns. PE also shows improvement, moving to sixth place, while SP remains at the bottom, reaffirming its inefficiency. Fig. 6.14 shows the regional distribution of the LCOH in Brazil.

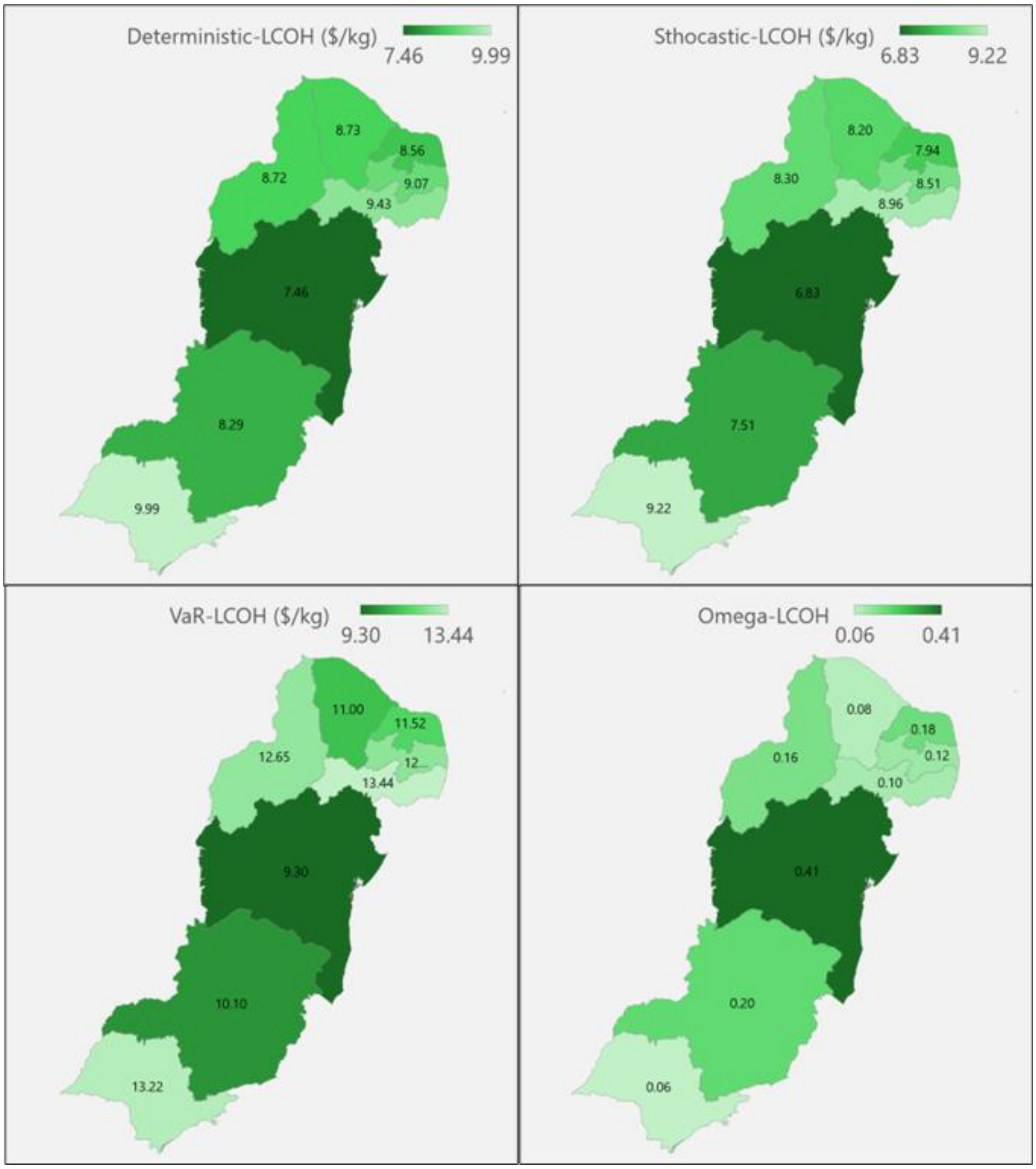


Fig. 6.14. The regional differences in the LCOHs by approach.

In conclusion, BA and MG appear as the most cost-effective and competitive states for hydrogen production across all approaches, displaying resilience to deterministic and stochastic conditions. RN state consistently goes well, maintaining a high ranking. The variability in CE's performance across different approaches highlights the importance of considering multiple risk factors in LCOH evaluations. Despite its low ranking in deterministic conditions, SP shows improvement under volatility measures, indicating potential under specific scenarios. This comprehensive analysis could highlight the importance of adopting multi-faceted approaches that effectively evaluate the economic efficiency and competitiveness of investment in hydrogen production.

6.7 Summary

This study provides an in-depth analysis of hydrogen production and the associated costs across various Brazilian states. The study involves the Monte Carlo simulation to evaluate the levelized cost of hydrogen LCOH, considering factors like stack efficiency, degradation rates, and utilization. Key findings highlight Bahia's highest hydrogen production capacity and São Paulo's lowest, with notable variability in production estimates among different states. The analysis also explores the financial and operational factors influencing LCOH, emphasizing the impact of inflation, exchange rates, and utilization rates. Risk assessments using VaR-LCOH and Omega-LCOH reveal significant cost variability and the need for robust financial strategies. This comprehensive evaluation aims to guide strategic planning and resource allocation for efficient and cost-effective hydrogen production in Brazil.

6.7.1 Simulations and framework

- Ten thousand simulations were conducted to analyze LCOH outcomes for each Brazilian state.
- The analysis focused on stack efficiency, degradation rate, and utilization, which are crucial for estimating hydrogen generation using electricity from PV systems.

6.7.2 State-wise production capacity

- Bahia (BA): Highest hydrogen production capacity at 4,320.27 tons/year.
- São Paulo (SP): Lowest production capacity at 3,055.07 tons/year.
- Piauí (PI): Highest variability in production (standard deviation 829.8 tons/year).
- Minas Gerais (MG): Lowest variability (standard deviation 464.1 tons/year).

6.7.3 Base case and mean values

- Bahia: The lowest base case LCOH is $7.46/kg, and the mean LCOH is $6.83/kg.

- São Paulo: Highest base case LCOH at $9.99/kg and mean LCOH at $9.22/kg.
- Most states show mean LCOH lower than the base case, indicating conservative estimates in base cases.

6.7.4 Statistical measures

- Standard Deviation: Bahia has the lowest ($1.48/kg), and Pernambuco is the highest ($2.46/kg).
- Variance: Reflects cost variability; Pernambuco and Paraíba show high variance.
- Minimum and Maximum Values: Bahia has a minimum of $1.99/kg and a maximum of $16.61/kg, while Paraíba shows a wide range from $2.36/kg to $29.36/kg.
- Skewness and Kurtosis: Positive skewness in all states indicates a longer right tail (higher-cost outliers); PB has the highest skewness and kurtosis, suggesting high-cost outliers and a significant risk of high costs.

6.7.5 Impact of financial factors

- Inflation Rate: Strong negative correlation with LCOH, indicating higher inflation reduces LCOH due to discounted future costs.
- Exchange Rate: Less significant impact than inflation; impacts the cost of imported equipment and materials.

6.7.6 Impact of physical and technical factors

- Utilization Rate: Significant negative correlation with LCOH; higher utilization reduces LCOH, especially in PE, RN, and PI.
- Solar Radiation: Limited direct impact on LCOH despite high PV potential; operational efficiency is extra critical.

6.7.7 Capital and Operational Costs

- PEM and PV Capital Costs: Positive correlation with LCOH; higher initial investments increase LCOH.
- O&M Costs: Positive correlation with LCOH; ongoing operational expenses significantly impact cost.

6.7.8 Risk Analysis – VaR

- VaR-LCOH represents the maximum expected cost under adverse conditions.

- Bahia: Lowest VaR-LCOH at $9.30/kg.
- Pernambuco: The highest VaR-LCOH is $13.44/kg, indicating substantial cost escalation risk.
- States with high VaR-LCOH require robust financial strategies to manage potential cost spikes.

6.7.9 Risk-Return Profile–Omega ratio

- The omega ratio compares probability-weighted gains to losses.
- Bahia: Omega value of 0.41, indicating inefficiency but less extreme than other states.
- São Paulo: Lowest Omega value of 0.06, reflecting severe inefficiency and high-cost instances.
- All states show Omega values below 1, indicating that losses outweigh gains, imposing better cost management strategies.

6.7.10 Conclusion

- The document analyzes hydrogen production and costs across Brazilian states, emphasizing the variability and uncertainty in production capacities and costs.
- Financial and operational efficiencies are critical in reducing LCOH.
- States like Bahia and Minas Gerais show more stable and predictable cost structures, making them attractive for investment.
- Effective financial management, particularly in managing inflation and operational efficiencies, is essential for optimizing hydrogen production costs.

7. THE STEF-H2V UNDER A PERSPECTIVE OF VARIABILITY AND UNCERTAINTY

This chapter presents an extension of the STEF-H2V model that applies 2D simulation to estimate the levelized cost of hydrogen (LCOH) to evaluate investment risks in renewable hydrogen production. The framework considers uncertainty and variability in TEA, providing a comprehensive financial risk assessment.

7.1 Background

Hydrogen has the potential to become a crucial interconnection component between energy systems for two main reasons: (1) its cross-sector ability to couple input energy to end-use applications that occur at different times and locations, and (2) its ability to enable clean and efficient end-use applications [266].

Efforts are necessary to enhance the hydrogen economy in the electrolysis chain, which covers the production, transport, storage, and last use of hydrogen in its most efficient form [1]. Using electrolyzers for hydrogen production has shown promise, providing services for smart grids and market participation [282]. However, this area requires more robust investigations and discussions regarding the technical-economic challenges of production technology and associated environmental carbon emissions, as well as integrating hydrogen resources for an economic evolution of hydrogen production under the levelized cost of hydrogen bias to reduce cost disparities [266], [282], [283].

This case study introduces a stochastic approach that uses 2D simulation to identify the potential areas with higher financial risk in investments related to renewable hydrogen. The research hypothesis in this chapter will start with an investigation through the proposed approach (as part of a framework) for renewable hydrogen production in Itajubá, Minas Gerais, Brazil, using the LCOH.

The motivation stems from the idea of recognizing and differentiating between uncertainty and variability in TEA, which is often disregarded and treated solely as uncertainty. Thus, the novelty of this work presents an approach that analyzes the probability of investment risk while characterizing this risk robustly through 2D simulation.

7.2 Case study: evaluating variability and uncertainty in hydrogen generation

This analysis is applied in a case study in Minas Gerais, Brazil, since PV generation has great potential in the country, with very representative PV generation in the state contributing to renewable hydrogen generation. However, solar radiation is not the only source of variability affecting hydrogen investments.

The case study assesses five other uncertainties to show how each one affects hydrogen investments financially.

Commonly, findings analyze the feasibility in different world regions, lacking in contemplating the causes of local uncertainties and variability. Such circumstances can change the attractiveness pattern concerning the expected return for hydrogen investments from one region to another. This case study investigates an expected LCOH estimate (deterministic and stochastic approaches). The results will compare the order of competitiveness for the deterministic and stochastic methods.

7.3 Techno-economic analysis criteria

Further to the breakdown of LCOH, the utilization of the 2D Monte Carlo method into STEF-H2V facilitates the identification of parameters that significantly impact the final LCOH through the differentiation of uncertainty from variability. For this case study, every input parameter of the model is randomly adjusted according to the values, and the resulting LCOH is computed for each iteration denoted by Eq. (7.1), which evaluates the present value of fixed and variable costs associated with hydrogen production per unit in \$/kg over the system's useful life [4], [5]:

$$LCOH = \frac{TOTEX_T}{\sum_{n=1}^{N} \frac{G_{H2}}{(1+r)^n}} = \frac{Total\ Lifetime\ Cost}{Total\ Lifetime\ Hydrogen} \tag{7.1}$$

where: $TOTEX_T$ is the total costs from the sum of CAPEX and discounted OPEX (US\$).

The incidence of solar radiation directly affects the current and voltage, affecting the generation of renewable hydrogen through PV electrolysis, as explained in Eq. (4.3) [211]:

$$PV_{eg} = \eta * \rho * A * (1 - \gamma) * (1 - \delta^{n-1}) \tag{5.3}$$

where: η is the PV cells efficiency (%); ρ is the local irradiation (kWh/m^2); A is the occupation area by the system (m^2); γ is the losses (≈19% [213]), and δ is the per year degradation factor, 0.25% [67], and n is the year.

Concerning the production of renewable hydrogen, the annual generation can be determined using Eq. (4.4) [149], [238]:

$$G_{H2} = \frac{t * P_{El} * u}{E_{El}} (1 - \delta)^{n-1} \tag{5.4}$$

where: G_{H2} is the hydrogen generation; t is the number of hours in the year (h); P_{El} is the electrolyzer power (kW); u is the electrolyzer utilization rate stated in a fraction; E_{El} denotes the electrolyzer electricity consumption (kWh/kg); δ is the system degradation rate (2% [216]), and n is the year.

This study uses a stochastic approach based on 2D simulation to assess the levelized cost of hydrogen (LCOH). This evaluation incorporates uncertainty and variability into six assumptions, as outlined in sub-section 6.4. Therefore, Eq. (6.4) describes the mathematical estimation of stochastic LCOH. [188]:

$$\widetilde{LCOH} = f\left(\widetilde{TOTEX}, \widetilde{G_{H2}}, \tilde{r}\right) \tag{7.4}$$

where: $\widetilde{LCOH}$ = probability distribution function for the LCOH outputs; $\widetilde{TOTEX}$ = probability distribution function for the TOTEX; $\widetilde{G_{H2}}$ = probability distribution function for hydrogen generation; $\tilde{r}$ = PDF for the discount rate.

7.4 Key parameters

The LCOH estimate considered a PEM electrolyzer with a range of 1.25 MW and a PV system of 2.5 MW. Table 7.1 displays the details of the used electrolyzer.

TABLE 7.1. PEM ELECTROLYZER DETAILS.

Parameter	**Valor**
Average daily solar radiation (kWh/m²)	4.99
PV system power (MW)	2.5
PV generation yearly (GWh)	3.66
Electrolyzer power (MW)	1.25
Output pressure (bar)	up to 35
Electrolyzer overall efficiency (%)	65
Hydrogen Production (kg/h)	20
Stack lifetime (h)	65,000
Electrolyzer electricity consumption (kWh)	1,200
Water consumption (m³/h)	0.34
Plant lifetime (year)	22
Daily operation time (h/day)	8
Compression system power (W)	500
Compression flow (kg/h)	5.09
Compressor electricity consumption (kWh)	0.5
Storage capacity (day)	3

Derived from: [191], [192], [194], [195], [199].

The assessment did not consider loan payments, debt interest, or non-cash deductions (i.e., depreciation and amortization). Therefore, Eq. (6.5) allows for the calculation of CAPEX.

$$CAPEX_T = CAPEX_{PV} + CAPEX_{El} + CAPEX_{Co} + CAPEX_{St} \tag{6.5}$$

$CAPEX_{El}$ is the electrolyzer investment cost taken by the electrolyzer power (1.25 kW) multiplied by the electrolyzer purchase cost of US$ per kW (1000 US$/kW) [193]. $CAPEX_{Co}$ is the compression system investment cost found by multiplying the number of compressors needed by the price of each compressor (130k US$) [194]. The number was calculated by dividing the plant's annual flow by the compressor's hourly flow (rounding up). $CAPEX_{St}$ is the storage capital cost estimated by the number of storage days multiplied by the storage cost (63 US$) [195]. $CAPEX_{PV}$ is the PV system investment cost calculated by the investment price per Wp in the installed power unit (0.77 US$/Wp [196]), multiplied by the PV cell power (345 Wp), and by the total of PV cells. Technical data of a PV cell were considered, with the subsequent parameters: Rated Power (Pot) = 345 Wp; η = 21%; A = 1.63m^2; δ = 0.25% per year [198].

Using Eq. (6.6), it is viable to calculate the OPEX, which refers to operational expenditure.

$$OPEX_n = OPEX_{PV} + OPEX_{El} + OPEX_{Co} + OPEX_{St} \tag{6.6}$$

where: $OPEX_{PV}$ = PV System O&M Cost; $OPEX_{El}$ = electrolyzer O&M cost included water and electricity consumption and electrolysis stack replacement. $OPEX_{Co}$ = compressor O&M Cost, and $OPEX_{St}$ is the storage system O&M Cost. Note that Brazilian currency (Real) was converted to US dollars (BRL to USD), where 1.00 USD was equivalent to 5.00 BRL. Next, Table 7.2 presents the input cost data used to estimate LCOH.

TABLE 7.2. INPUT PARAMETERS TO ESTIMATE LCOH.

Parameter	**Note**	**Valor**	**Ref.**
Solar PV price (US$/Wp)	Total system cost + balance of the system (BOS)	0.77	[196]
PV OPEX (US$)	% of the PV system CAPEX	0.5	[202]
PEM electrolyzer CAPEX (US$/kW)	Includes stack and BOS	1000	[193]
PEM electrolyzer OPEX (US$)	% of the PEM electrolyzer CAPEX	2	[203]
Stack replacement cost (US$/kW)	Stack lifetime = 65000 h @ full load for PEM electrolyzer	400	[193]
Water Price (US$/m³)	Based on the local scenario	2.43	[204]
Electricity Price (US$/kWh)	Based on the local scenario	3.38	[205]
Compressor CAPEX (US$)	Unit price	1,300 k	[194]
Compressor OPEX (US$)	% of the Compressor CAPEX	0.8	[194]
Storage CAPEX (US$/ Nm³)	Storage days X storage cost	63	[195]
Storage OPEX (US$/day)	% of the Storage CAPEX	0.5	[207]
Discount rate (%)	Based on the local scenario	4	[208]

The STEF-H2V in this study incorporates a stochastic approach to reproduce uncertainty and variability in the LCOH. The Excel add-in at Crystal Ball® [226] was used to conduct the 2D simulations. Fig. 7.1 displays an illustration of the framework.

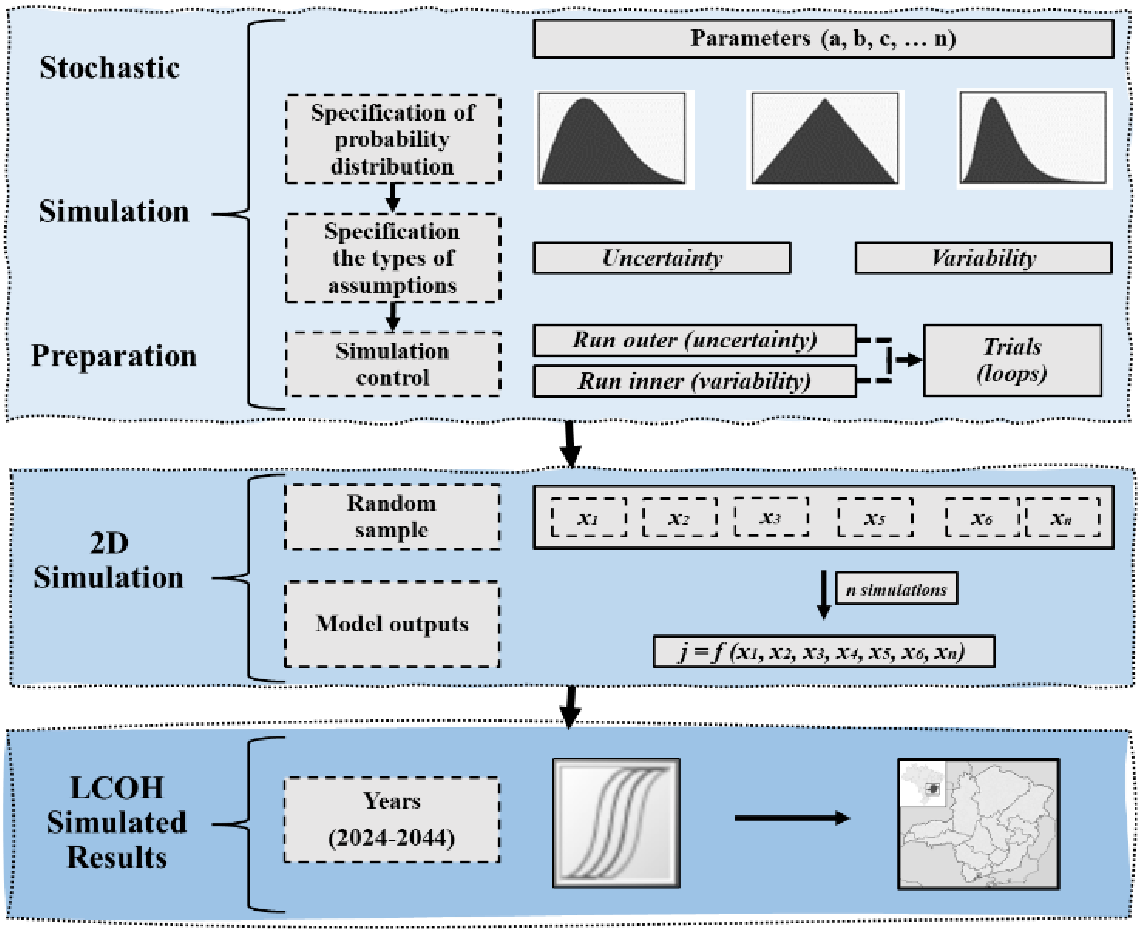


Fig. 7.1. Framework overview with a stochastic approach to estimate LCOH.

In the first phase, the STEF-H2V specifies probability distributions for key variables influencing the LCOH estimation. These distributions are chosen based on the variables' impact on hydrogen production investments. The included assumptions encompass uncertainty and variability, each represented by a distinct probability distribution function (see Table 6.3).

TABLE 7.3. PROBABILITY DISTRIBUTION ASSUMPTIONS.

Variable	**Probability Distribution**	**Source of Variation**
Electrolyzer Cost (US$/kW)	Beta-PERT (500; 1164.8; 2097.6) [3]	Uncertainty
System Efficiency (%)	Triangular (52; 65; 78)	Uncertainty
Daily utilization rate (h)	Triangular (6.5; 8.0: 9.5)	Variability
Average daily solar radiation (kWh/m^2)[4]	Weibull (4.24; 0.82; 5.27709)	Variability
Solar PV price (US$/kW)	Triangular (0.62; 0.77; 0.92)	Uncertainty
Discount rate (%)	Triangular (8.4; 10.5; 12.6)	Uncertainty

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[3] Based on Ref. [149].

[4] Goodness-of-fit is executed based on Anderson Darling’s test at Crystal Ball® to check the best distribution.

For uncertainty, assumptions such as electrolyzer cost, system efficiency, solar PV price, and discount rate are modeled using Beta-PERT and Triangular distributions. These distributions capture the uncertainty associated with these variables due to a lack of precise information or fluctuations in market conditions. Conversely, distributions such as Triangular and Weibull represent variability assumptions, such as daily utilization rate and average daily solar radiation, respectively. These distributions account for the inherent variability in system performance factors, which can affect hydrogen production over time.

In order to maintain the accuracy and reliability of the stochastic simulation, these controls determine the quantity of random samples generated and the number of repetitions performed. This approach ensures the robustness of the results obtained. Simulation control parameters, such as the number of iterations and simulations, are also defined in this phase, where the number of trials for the outer (uncertainty) simulation and inner (variability) simulation was 50 outer trials and 1000 inner trials, resulting in 50000 values of LCOH for 1000 interactions.

In the second phase, the STEF-H2V is performed using a 2D Monte Carlo approach, which involves generating random samples from the specified probability distributions for each assumption in the previous phase. These random samples represent different system variables scenarios, capturing uncertainty and variability. For each simulation iteration, the model calculates the LCOH based on the sampled values of the input variables. The model outputs, including LCOH values, are recorded for each simulation run. This process is repeated for a predetermined number of simulations (n simulations), ensuring a comprehensive exploration and capturing the full range of potential outcomes.

After completing the 2D Monte Carlo simulation phase, the STEF-H2V produces a set of simulated results for the LCOH over the specified time period (2024-2044). These results encompass a range of LCOH values corresponding to different combinations of input variable scenarios, providing a comprehensive understanding of the economic viability of renewable hydrogen production in Itajubá, considering both uncertainty and variability in key factors influencing LCOH. Decision-makers can use these results to assess the risk and potential return on investment associated with regional hydrogen production projects. Furthermore, the simulated outcomes can be examined to identify trends, patterns, and sensitivities in estimating LCOH over a period. This information can help stakeholders develop strategies to mitigate risks, optimize resource allocation, and maximize the economic benefits of renewable hydrogen production even in different contexts.

7.5 Insights and discussion remarks

The 2D simulation reliably estimates the variables and potential endogenous between these stochastically simulated sources of variation by contemplating uncertainty and variability. 1000 interactions (inner loop) and 50 simulations (outer loop) were conducted [108]. This resulted in 50,000 potential LCOH values, as depicted in Fig. 6.2, representing all possible LCOH outcomes.

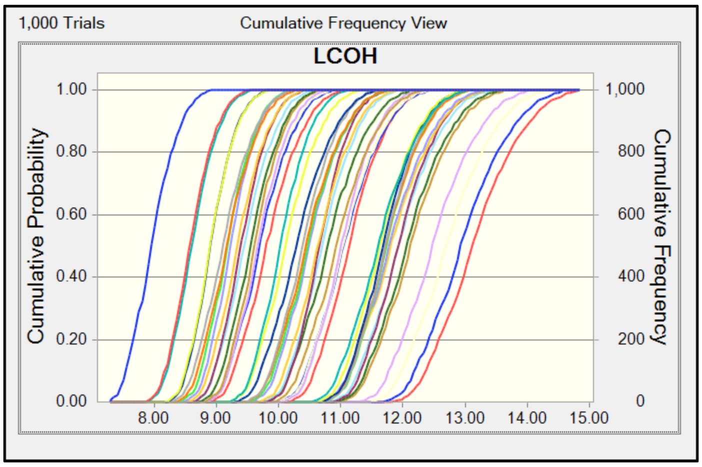


Fig. 7.2. Framework overview with a stochastic approach to estimate LCOH.

The proposed framework allows the creation of a series of LCOH curves, accounting for the uncertainties and variability. If the uncertainty interval is more significant than the variability, it shows that risk events will impact the total uncertainty of the strategic investment more than the variability, or vice versa. The overlay chart in Fig. 7.2 displays the risk curves (cumulative distributions) for different uncertainty assumption values, with most of the curves spread apart, showing that the risk events related to uncertainty affect LCOH much more than the variability associated with solar radiation and utilization rate.

In the risk assessment literature, the curves are often called the alternate realizations of the population risk valuation. Using trend charts (Fig. 7.3) can also achieve the presentation of those curves, showing the certainty bands for the percentiles of the risk curves.

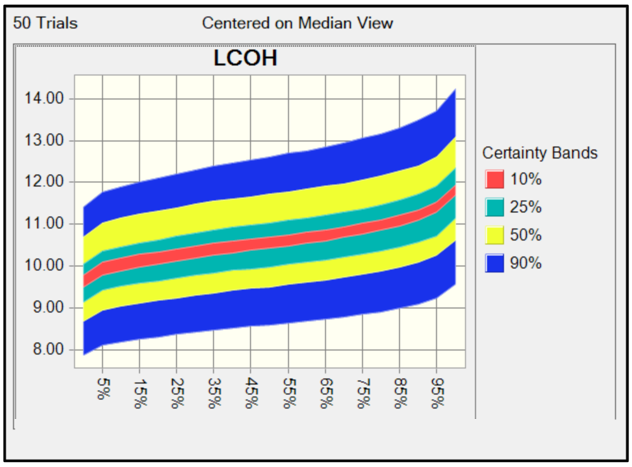
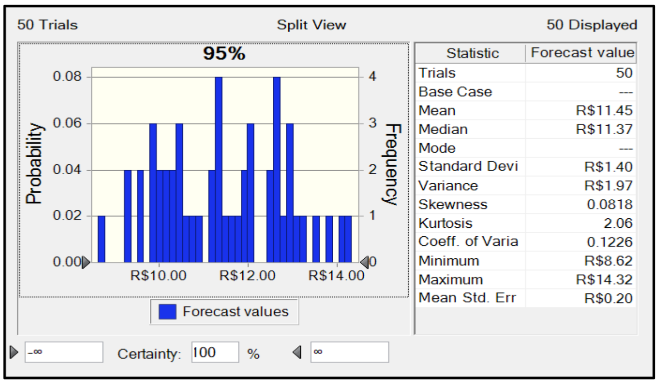


Fig. 7.3. Trend chart certainty bands

Concerning the LCOH, the best way is to establish and apply effective mitigation by accurately predicting the parameters such as prices, inflation, capacity, CAPEX, and OPEX. The capacity shows the amount of uncertainty at each percentile level for all the probability distributions. The LCOH curves could make effective strategic decisions using probability criteria, giving deep insights into analyzing the sources of variation in renewable hydrogen investment. It will precisely determine whether variability or uncertainty will impact LCOH more.

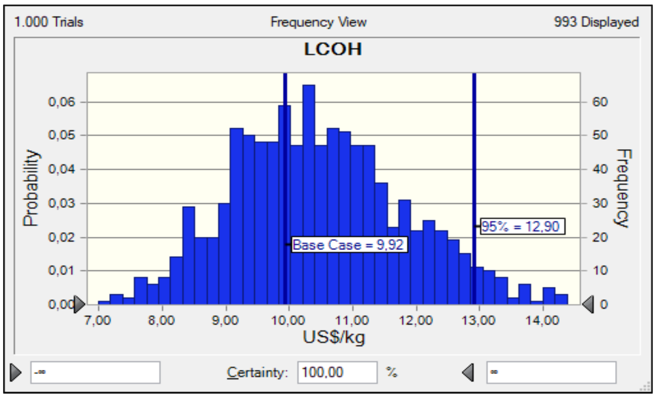
By utilizing the analysis percentile levels, specifically the 95th percentile, it is possible to observe the forecast related to the 95th percentile. In Fig. 7.4, the number of 95th percentiles in the prediction shows the attempts. Then, it is possible to compare the two-dimensional simulation results with a one-dimensional simulation of the same risk view, as in Fig. 7.5.



Statistic	Forecast value
Trials	50
Base Case	---
Mean	R$11.45
Median	R$11.37
Mode	---
Standard Devi	R$1.40
Variance	R$1.97
Skewness	0.0818
Kurtosis	2.06
Coeff. of Varia	0.1226
Minimum	R$8.62
Maximum	R$14.32
Mean Std. Err	R$0.20

-∞ Certainty: 100 % ∞

Fig. 7.4. 95th percentile forecast statistics.



-∞ Certainty: 100,00 % ∞

Fig. 7.5. Forecast for one-dimensional simulation

The mean LCOH at the 95th percentile in Fig. 7.3, 95th percentile forecast statistics, 11.13 US$/kg, is lower than the 95th percentile risk of the one-dimensional simulation shown in Fig. 7.5, Prediction plot for one-dimensional simulation at 12, 90 US$, which is also upper than in the base case. This shows the tendency of one-dimensional simulation results to overestimate the LCOH value, especially for highly skewed distributions. By treating all variables in the same way, instead of separating the two types, the one-dimensional simulation appears to have overestimated the level of risk, resulting in LCOH values higher than expected. In contrast, the 2D simulation, which addressed sources of variation more accurately, produced a more realistic simulation result.

Comparing Fig. 6.4 and Fig. 7.5, it is clear that the one-dimensional simulation overestimates the LCOH value, particularly for highly skewed distributions. This is clear from the fact that the mean LCOH at the 95th percentile in Fig. 6.4 is lower than the 95th percentile risk in Fig. 7.5. The one-dimensional simulation predicts a 95th percentile risk of 12.90 US$/kg, which is higher than the base case, suggesting that it has overestimated the level of risk.

In contrast, the 2D simulation, which precisely incorporates sources of variation, produces a more verisimilar simulation outcome. By giving equal consideration to all variables, it is apparent that the one-dimensional simulation has overestimated the risk level, resulting in higher-than-expected LCOH values. Consequently, it is apparent that opting for the 2D simulation is the preferred choice for obtaining precise and dependable outcomes.

7.6 Summary of results and analysis

The present study aimed to analyze the economic potential stochastically from the perspective of uncertainty and variability from the LCOH view. The idea is investigate the risk of investments in renewable hydrogen, where the deterministic and unidimensional LCOH presented in the literature cannot identify this risk. A comparative analysis examined the differences in risk classification between the approaches used to estimate the LCOH. The results revealed that the investment risk could differ significantly even with the high renewable energy potential.

Solar radiation, characterized as variability, did not significantly affect LCOH like other uncertainties, showing that the risk events associated with uncertainty influence LCOH much more than the variability. This outlines the valuable contrast of using 2D simulation as an advanced tool for risk analysis that differentiates uncertainty from variability for investments in renewable hydrogen, and that does not occur in a deterministic and one-dimensional perspective.

This case study limits the stochastic LCOH evaluation from the perspective of uncertainty and risk using 2D simulation. The 2D simulation can evaluate LCOH in other localities and different scales. Future works on this test case can focus on merging the approach used by the framework with risk measures such as the Omega ratio and Conditional Value at Risk. This will allow for a great investigation of investment risk and optimization for optimal LCOH analysis of different sources to produce hydrogen. This would significantly advance countries like Brazil, where the hydrogen infrastructure is still being built, and can contribute to the role of essential players worldwide by producing renewable hydrogen.

8. LIMITATIONS, EXTENSIBILITY, AND FUTURE RESEARCH

This comprehensive chapter addresses the limitations, extensibility, and future research directions for the proposed stochastic techno-economic framework. It acknowledges the constraints faced during the study, suggests ways to expand and adapt the framework, and outlines potential areas for future investigation to enhance the understanding and implementation of green hydrogen projects.

8.1 Limitations

This study, which presents a stochastic techno-economic framework for green hydrogen investments under uncertainty and risk conditions, identifies several limitations. Recognizing these limitations is critical for understanding the scope and context of the research and identifying areas for future improvements and investigations.

A significant limitation of this research stems from the availability and quality of the data used, especially since it involves complex data and econometrics. The stochastic models developed depend heavily on accurate and comprehensive data sets for inputs such as solar irradiation, electrolyzer efficiency, utilization, and financial parameters. However, data availability varies significantly across different regions and periods, which can affect the accuracy and reliability of the results. Some data may be outdated or incomplete, introducing potential biases and uncertainties in the model outputs. Additionally, the lack of standardized data collection and reporting practices further complicates acquiring high-quality data. Compiling and complementing these data sets is necessary for improving model robustness.

The framework was built to use several assumptions that may not hold universally. For instance, the assumption of constant efficiency and degradation rates for photovoltaic PV panels and electrolyzers over their lifetimes may not accurately reflect real-world conditions, where technology improvements and maintenance activities can alter these parameters. Economic assumptions, such as discount rates and capital expenditure (CAPEX) estimates, are based on current market conditions, which can change due to technological advancements and policy changes. Although these assumptions are essential for simplifying the model, they restrict the extent to which the results can be applied and generalized. The framework might not fully capture the dynamic nature of technological and economic environments, which can influence the outcomes.

The case studies and simulations in this research are specific to certain regions in Brazil. While these regions were selected to represent diverse climatic and economic conditions, the findings may not be directly transferable to other regions or countries with different environmental, economic, and policy contexts. Therefore, caution should be employed when generalizing the results beyond the studied areas. The regional specificity highlights the need for localized studies that can account for different areas' unique characteristics and conditions. This limitation underscores the importance of conducting similar analyses in different global contexts to validate and refine the framework, as it was done for its application in a case study in Germany.

Clean hydrogen technology is still evolving, and inherent uncertainties are associated with key technologies' performance and cost trajectories, such as electrolyzers and renewable energy systems. While the stochastic models aim to capture some of these uncertainties, unexpected technological breakthroughs or setbacks could significantly modify the projected outcomes. The fast innovation process in renewable hydrogen technology means that assumptions and predictions made today may quickly become obsolete. This technological uncertainty imposes continuous monitoring and updating of the framework to ensure it reflects the latest advancements and trends.

The economic analysis within this framework is subject to financial market fluctuations that can impact key financial parameters, such as inflation, exchange rates, and interest rates. These fluctuations can influence the cost of capital, operational expenses, and overall project feasibility. While the stochastic approach attempts to incorporate variability and uncertainty, the volatile nature of financial markets can introduce additional layers of complexity and risk that are challenging to model accurately. Future research should consider more sophisticated financial models that can dynamically adjust to market changes.

8.2 Extensibility

Despite these limitations, the proposed STEF-H2V offers several possibilities for extensibility and adaptation to other contexts and applications. The framework's flexibility and robustness make it a valuable tool for a wide range of interested parties in green hydrogen investments.

The framework can be extended by integrating additional risk measures such as Conditional Value at Risk (CVaR), Beta measure, Sharpe ratio, and Sortino ratio. These measures provide different perspectives on investment risk and can help investors make more informed decisions by considering adverse events' prospects and impact. The framework can offer a more comprehensive risk assessment by incorporating these measures, encompassing the correlation and causality of variables used as assumptions in Monte Carlo simulations. This integration can enhance decision-making by providing a multi-dimensional risk view, encompassing statistical probability and financial impact.

The STEF-H2V can be adapted to different geographical regions by updating the input data to reflect local conditions. This includes regional solar irradiation data, local economic parameters, region-specific technological performance data, and large-scale production. By customizing the inputs, the framework can evaluate the techno-economic feasibility of green hydrogen projects in several parts of the world, enabling broader applicability and relevance. Such adaptability ensures that the framework remains useful and accurate across diverse settings, accommodating the unique characteristics of each region.

As new technologies emerge, the framework can be updated to incorporate these advancements and different electrolyzer technologies. For example, developing more efficient and cost-effective electrolyzers or advancements in hydrogen storage technologies can be included in the model to reflect the latest technological trends. This adaptability ensures that the framework remains relevant and valuable in the face of rapid technological changes. Regular updates and revisions to the model will help maintain its accuracy and relevance.

Incorporating sophisticated financial instruments and strategies can enhance the framework's financial modeling capabilities. This includes using advanced conditions and avoiding risks, scenario analysis for extreme market conditions, and integrating real options analysis to evaluate the flexibility of investment decisions. By enhancing financial modeling, the framework can provide a more robust analysis of the economic viability and risk profile of green hydrogen investments, helping investors explore the complexities of financial markets.

8.3 Future research

The findings and limitations of this study suggest several directions for future research. By addressing these areas, researchers can build upon the current work to further enhance the understanding and implementation of green hydrogen investments under uncertain and risky conditions.

Future research should focus on improving the availability and quality of input data. This can be achieved by developing more comprehensive and standardized data collection protocols and using advanced data analytics and machine learning techniques to process and validate the data. High-quality data is crucial for accurate model predictions and reliable decision-making. Collaborations between academia, industry, and government agencies can facilitate the collection of more extensive and reliable data sets, enhancing the robustness of the models.

There is a requirement to develop dynamic and adaptive modeling approaches to better capture changing conditions and uncertainties. This includes real-time data and feedback mechanisms that allow the models to adjust to new information and changing market conditions. Such approaches can improve the robustness and responsiveness of the stochastic techno-economic framework. Adaptive models that can learn and evolve with new data will be better equipped to handle the complexities and uncertainties of green hydrogen projects, providing more accurate and sensible insights.

Future studies should also explore the impact of policy and market dynamics on hydrogen investments. This comprises analyzing the effects of subsidies, carbon pricing, and other regulatory measures on the economic viability of hydrogen projects. Understanding these associations can provide valuable insights for policymakers and investors looking to support the growth of the hydrogen economy. Policy analysis should consider both the direct and indirect effects of regulatory measures and potential unintended consequences to assess policy impacts comprehensively.

Conducting comparative studies across different regions can help identify best practices and key factors that influence the success of green hydrogen projects. By comparing the techno-economic performance of projects in diverse contexts, researchers can identify common challenges and opportunities, informing better investment strategies and policy decisions. Comparative studies can also reveal regional strengths and weaknesses, guiding targeted interventions and supporting measures to optimize hydrogen infrastructure development globally.

Future research should focus on developing technological roadmaps for the green hydrogen sector. These roadmaps can outline the expected technological advancements, future hydrogen demand, potential breakthroughs, and key indicators required to achieve widespread adoption and commercialization of clean hydrogen technologies. By providing a clear vision and strategic direction, technological roadmaps can help guide research, development, and investment efforts, ensuring that the hydrogen sector continues to evolve and mature, as occurred in the photovoltaic sector.

Besides economic and technical considerations, future research should incorporate comprehensive environmental impact assessments of green hydrogen projects. This involves evaluating the lifecycle emissions, resource use, and potential ecological impacts of production, storage, and utilization. By integrating environmental impact assessments into the techno-economic analysis, researchers can provide a more holistic evaluation of the projects, ensuring that they contribute to sustainable development goals.

9. PHILOSOPHICAL CONSIDERATIONS

This chapter reflects on philosophical themes of ethics, safety, environment, privacy, and collective responsibility with the stochastic techno-economic framework for green hydrogen projects presented in this thesis. Addressing these philosophical topics makes it possible to understand the implications of technological innovations and foster a more holistic approach to sustainable development.

9.1 Research and technological developments

In the sphere of research and technological advancements, understanding the ethical and philosophical dimensions is crucial. Ethical considerations in technology ensure that developments are beneficial and do not cause harm, including ensuring the safety and well-being of society, minimizing environmental impact, and protecting privacy. Technological dilemmas often arise when balancing these aspects against innovation and progress. For instance, the rapid development of AI and robotics raises questions about job displacement, data security, potential misuse, and safety, which is paramount in technological projects. The development of the green hydrogen industry must prioritize and evaluate systems to prevent harm to users and the environment, considering safety standards. Environmental ethics in technology focus on sustainable practices and reducing carbon footprints, and green hydrogen projects, for example, aim to produce clean energy, thus addressing environmental concerns associated with traditional fossil fuels.

Privacy has become a critical ethical issue with the rise of digital technologies, especially in ensuring that personal data is protected and used responsibly, which is a significant challenge. Everyone involved must design and evaluate systems that respect user privacy while enabling technological benefits, requiring a balance between functionality and ethical responsibility. The same is applied to ethical approaches in technology, which can be categorized into several types, including virtue ethics, consequentialism, and deontological ethics.

Green hydrogen projects and investments require not only technical and economical aspects. A diverse knowledge set spans various disciplines, including arithmetic, spatial, physical, biotic, sensitive, logical, historical, linguistic, social, aesthetic, legal, and trust knowledge, where each type of knowledge contributes to the holistic understanding required for successful project development. Integrating these different types of knowledge is essential in technological projects. For instance, developing a green hydrogen project requires also an understanding of environmental impact, legal regulations, and social implications. Despite the breadth of knowledge required, there are limitations in what can be known and predicted in technological projects. Uncertainties and risks are inherent, and engineers and decision-makers must develop frameworks to manage these uncertainties. The stochastic techno-economic framework (STEF-

H2V) for green hydrogen projects addresses these limitations by incorporating financial risk measures and stochastic modeling techniques.

Technology is not just a set of tools and systems but a social function that influences and is influenced by culture, politics, and globalization [284]. The investments in hydrogen technology must be aware of their work's cultural power and geopolitical implications related to the impact of technology on different societies and ensure that technological advancements do not perpetuate inequalities or imperialism. Studying real-world case studies and emerging engineering projects in green hydrogen could take advantage of combining sustainability initiatives to help illustrate the application of ethical principles in practice in smart grids and smart cities, demonstrating how green hydrogen technologies can be designed to enhance urban living while addressing ethical and social challenges. Ultimately, it is evident that considering philosophical aspects in research and technological developments is crucial for the creation of innovative and functional technologies that are also ethically responsible. By integrating diverse knowledge, managing uncertainties, and adhering to ethical principles, we can ensure the development of a green hydrogen economy that benefits society as a whole.

10. CONCLUDING REMARKS

The STEF-H2V developed in this thesis dissertation presents a comprehensive methodology for evaluating the viability and risks associated with green hydrogen investments and represents a significant advancement in the field. This framework integrates stochastic modeling and advanced financial risk measures to investigate the uncertainties inherent in green hydrogen technologies. The framework's application through various case studies provides a detailed understanding of the economic and technical dynamics, offering valuable insights for government, investors, and policymakers. STEF-H2V leveraged Monte Carlo simulations to generate a range of outcomes for key financial and operational parameters. This approach allows for a more comprehensive understanding of the potential variability in project performance, moving beyond traditional deterministic methods. By incorporating measures such as Value-at-Risk (VaR) and Omega ratio, the framework provided a robust assessment of financial risks, helping investors to quantify and manage potential losses more effectively.

This research's systematic literature review (SLR) aimed to investigate the financial indicators used for investment analysis in green hydrogen projects. The findings provide a comprehensive overview of the current state of knowledge in this emerging field, highlighting both the progress made and the gaps that still need to be addressed. Overall, the SLR findings emphasize the importance of adopting a multi-faceted approach to techno-economic analysis in green hydrogen projects. While traditional financial indicators like LCOH, NPV, and Payback Period are valuable, they must be complemented with stochastic methods and advanced risk measures to provide a comprehensive assessment. The identified gaps in the literature highlight the relevance of this thesis, showing critical areas for future research, including the integration of dynamic and adaptive modeling techniques, enhanced data collection and quality, and comprehensive policy and market analyses. The systematic literature review offered valuable insights into the current practices and gaps in green hydrogen investment analysis. By addressing these gaps and adopting a more integrated approach, this study can significantly enhance the robustness and reliability of techno-economic evaluations, ultimately supporting the growth and success of green hydrogen as a basis of sustainable energy systems.

Chapter 4 applies the framework to a case study of distributed green hydrogen generation in Brazil and Germany. The results highlight the economic potential of these projects, showing that even under varying conditions of uncertainty and risk, green hydrogen can be a viable investment. The deterministic analysis provided a foundational understanding, while the stochastic analysis revealed a spectrum of outcomes, emphasizing the need for considering variability in financial and operational parameters. Incorporating value-at-risk (VaR) in the risk analysis allowed for quantifying potential financial losses and offering a more straightforward project risk profile.

Chapter 5 extends the framework to explore the gap in techno-economic analysis for green hydrogen investments by integrating financial risk management. This chapter underscores the importance of a holistic approach to techno-economic analysis, including detailed evaluations of capital expenditures (CapEx), operational expenditures (OpEx), and revenue streams. The case study illustrates that incorporating financial risk measures (Omega ratio and VaR) leads to a more realistic project viability assessment. Sensitivity analysis identifies key drivers, such as inflation and utilization rates, providing actionable insights for stakeholders to optimize their investment decisions.

Chapter 6 examines the framework's effectiveness under varying conditions of variability and uncertainty in a 2D stochastic simulation for hydrogen generation. The case study presented in this chapter evaluates how fluctuations in key variables, such as uncertainties and variabilities, electrolyzer cost, daily utilization rate, and average daily solar radiation, impact project feasibility. The results show that the stochastic framework effectively captures the range of outcomes, offering a resilient and adaptable approach to project evaluation. This chapter reinforces the significance of understanding short-term variability and long-term uncertainties to manage risks better and optimize investments.

The findings from these chapters collectively underscore the transformative potential of green hydrogen as a sustainable energy solution. Despite high initial costs and technological uncertainties, the techno-economic analysis reveals that green hydrogen projects can achieve economic viability under favorable conditions. Supportive policies and market mechanisms are crucial in mitigating financial risks and encouraging investment in this sector. Integrating advanced risk measures and stochastic modeling techniques provides a comprehensive financial landscape view, enabling better risk management and decision-making.

Several limitations of this research must be acknowledged. The reliance on regional data and specific technological assumptions limits the generalization of the findings. As green hydrogen technologies and market conditions evolve, continuous updates to the models are necessary to maintain their relevance and accuracy. Future research should focus on improving data quality, developing adaptive modeling techniques, and exploring the interactions between policy frameworks and market dynamics. Comparative studies across different regions and comprehensive environmental impact assessments will further enrich the understanding and applicability of the framework.

The extensibility of the framework offers opportunities for future research and application. Integrating additional risk measures can provide a more comprehensive risk assessment. Adapting the framework to different geographical regions by updating the input data to reflect local conditions can broaden its applicability and relevance. Incorporating emerging technologies into the models ensures the framework remains up-to-date with the latest advancements, providing stakeholders with accurate information for decision-making. Future research should also focus on developing dynamic and adaptive modeling approaches that better capture changing conditions and uncertainties. This involves encompassing real-time data and feedback mechanisms to enhance the robustness and responsiveness of the techno-economic framework. Policy and market analysis should explore the impact of subsidies, carbon pricing, and other regulatory measures on the economic viability of green hydrogen projects, providing valuable insights for policymakers and investors.

Comparative studies across different regions can help identify best practices and key factors influencing the success of green hydrogen projects. By comparing the techno-economic performance of projects in diverse contexts, researchers can identify common challenges and opportunities, informing better investment strategies and policy decisions. Developing technological roadmaps for the green hydrogen sector can outline expected advancements, potential breakthroughs, and key milestones, guiding research, development, and investment efforts. Besides economic and technical considerations, future research should incorporate comprehensive environmental impact assessments of green hydrogen projects. Evaluating lifecycle emissions, resource use, and potential ecological impacts can provide a more holistic evaluation of green hydrogen projects, ensuring they contribute to sustainable development goals.

Overall, the STEF-H2V provides a powerful tool for evaluating green hydrogen investments under uncertainty and risk. By addressing the limitations of traditional deterministic approaches and incorporating advanced risk management techniques, STEF-H2V enhances the robustness and reliability of techno-economic evaluations, supporting informed decision-making and contributing to the sustainable growth of the green hydrogen sector. In summary, this thesis significantly advances green hydrogen investment analysis by providing a detailed and adaptable framework for evaluating projects under uncertainty and risk conditions. The insights from the case studies in chapters 4, 5, and 6 offer valuable guidance for policymakers and investors, highlighting green hydrogen projects' economic and technical aspects. By addressing the identified limitations and pursuing the suggested future research directions, stakeholders can enhance the robustness and reliability of green hydrogen investments, contributing to a more sustainable and resilient energy system. The continuous evolution of this framework, informed by ongoing research and real-world applications, will ensure its relevance and utility in promoting the adoption and success of green hydrogen projects globally.

11. APPENDIX A. LIST OF PAPERS AND QUALITY SCORES

TABLE 11.1. LIST OF ARTICLES REVIEWED ALONG WITH THEIR QUALITY SCORES AND NUMBER OF CITATIONS.

Title	**ID**	**Quality Score**
A combined heat and green hydrogen (CHH) generator integrated with a heat network	[285]	5.0
A levelized cost of hydrogen (LCOH) comparison of coal-to-hydrogen with CCS and water electrolysis powered by renewable energy in China	[203]	7.5
A Techno-Economic Analysis of solar hydrogen production by electrolysis in the north of Chile and the case of exportation from Atacama Desert to Japan	[178]	6.5
A techno-economic perspective on solar-to-hydrogen concepts through 2025	[286]	6.5
A thorough investigation of solar-powered hydrogen potential and accurate location planning for big cities: A case study	[287]	4.0
An economic investigation of the wind-hydrogen projects: A case study	[288]	4.5
Analysis and techno-economic assessment of renewable hydrogen production and blending into natural gas for better sustainability	[75]	5.0
Analyzing the levelized cost of hydrogen in refueling stations with on-site hydrogen production via water electrolysis in the Italian scenario	[75]	6.5
Assessment of offloading pathways for wind-powered offshore hydrogen production: Energy and economic analysis	[289]	8.0
Assessment of offshore liquid hydrogen production from wind power for ship refueling	[290]	5.5
Assessment of the Potential for Green Hydrogen Fuelling of Very Heavy Vehicles in New Zealand	[291]	6.0

Title	ID	Quality Score
Assessment of wind-to-hydrogen (Wind-H2) generation prospects in the Sultanate of Oman	[169]	6.5
Biogas reforming integrated with PEM electrolysis via oxygen storage process for green hydrogen production: From design to robust optimization	[292]	7.5
Case study on the benefits and risks of green hydrogen production co-location at offshore wind farms	[293]	5.0
Cogeneration of green hydrogen in a cascade hydropower plant	[294]	6.5
Combined Oscillating Water Column & hydrogen electrolysis for wave energy extraction and management. A case study: The Port of Motril (Spain)	[295]	6.0
Conditioned hydrogen for a green hydrogen supply for heavy duty-vehicles in 2030 and 2050 – A techno-economic well-to-tank assessment of various supply chains	[296]	5.0
Co-production of electricity and hydrogen from wind: A comprehensive scenario-based techno-economic analysis	[297]	6.5
Country-specific cost projections for renewable hydrogen production through off-grid electricity systems	[298]	6.0
Critical assessment of the production scale required for fossil parity of green electrolytic hydrogen	[299]	5.0
Decarbonization of natural gas systems in the EU – Costs, barriers, and constraints of hydrogen production with a case study in Portugal	[300]	6.0
Development of electrolysis technologies for hydrogen production: A case study of green steel manufacturing in the Russian Federation	[165]	6.5
Economic and environmental analysis for PEM water electrolysis based on replacement moment and renewable electricity resources	[301]	8.5

Title	ID	Quality Score
Economic and technological feasibility of using power-to-hydrogen technology under higher wind penetration in China	[302], [303]	6.0
Economic assessment of a renewable energy-electricity-hydrogen system considering environmental benefits	[304]	5.5
Economic assessment of hydrogen production from sea water using wind energy: A case study	[305]	5.0
Economic assessment of hydrogen production from solar driven high-temperature steam electrolysis process	[306]	7.0
Economic feasibility studies of high pressure PEM water electrolysis for distributed H2 refueling stations	[307]	6.5
Effect of Emission Penalty and Annual Interest Rate on Cogeneration of Electricity, Heat, and Hydrogen in Karachi: 3E Assessment and Sensitivity Analysis	[308]	4.5
Evaluating an economic application of renewable generated hydrogen: A way forward for green economic performance and policy measures	[309]	4.5
Evaluation of hydrogen production by wind energy for agricultural and industrial sectors	[310]	5.5
Evaluation of levelized cost of hydrogen produced by wind electrolysis: Argentine and Italian production scenarios	[210]	6.0
Evaluation of the introduction of a hydrogen supply chain using a conventional gas pipeline–A case study of the Qinghai–Shanghai hydrogen supply chain	[311]	5.5
Exploring the feasibility of green hydrogen production using excess energy from a country-scale 100% solar-wind renewable energy system	[312]	7.0

Title	**ID**	**Quality Score**
Feasibility study of large scale hydrogen power-to-gas applications and cost of the systems evolving with scaling up in Germany, Belgium and Iceland	[313]	5.5
Green hydrogen for industrial sector decarbonization: Costs and impacts on hydrogen economy in qatar	[167]	6.0
Grid scale energy storage: Modeling of electrolyzer-fuel cell combination and comparison with flow batteries	[314]	5.0
Grid-connected hydrogen production via large-scale water electrolysis	[315]	6.5
Hydrogen as energy carrier: Techno-economic assessment of decentralized hydrogen production in Germany	[200]	6.0
Hydrogen costs from water electrolysis at high temperature and pressure	[316]	6.0
Hydrogen from offshore wind: Investor perspective on the profitability of a hybrid system including for curtailment	[317]	7.5
Hydrogen production via using excess electric energy of an off-grid hybrid solar/wind system based on a novel performance indicator	[318]	5.5
Hydrogen refueling station networks for heavy-duty vehicles in future power systems	[319]	6.0
Integration of renewable energies using the surplus capacity of wind farms to generate H2 and electricity in Brazil and in the Rio Grande do Sul state: energy planning and avoided emissions within a circular economy	[51]	5.5
Investment opportunities: Hydrogen production or BTC mining?	[320]	6.5
Large-scale hydrogen production via water electrolysis: a techno-economic and environmental assessment	[296], [321]	6.5

Title	ID	Quality Score
Large-Scale Maritime Transport of Hydrogen: Economic Comparison of Liquid Hydrogen and Methanol	[24]	7.0
Levelized Cost of Hydrogen Calculation from Off-Grid Photovoltaic Plants Using Different Methods	[22]	5.0
Levelized cost of hydrogen for refueling stations with solar PV and wind in Sweden: On-grid or off-grid?	[76]	6.0
Life cycle cost analysis: A case study of hydrogen energy application on the Orkney Islands	[322]	7.5
Life cycle cost assessment of wind power–hydrogen coupled integrated energy system	[323]	5.5
Marketability analysis of green hydrogen production in Denmark: Scale-up effects on grid-connected electrolysis	[324]	6.5
Membraneless electrolyzers for the production of low-cost, high-purity green hydrogen: A techno-economic analysis	[325]	6.0
Mining Nontraditional Water Sources for a Distributed Hydrogen Economy	[326]	6.0
Modelling Decentralized Hydrogen Systems: Lessons Learned and Challenges from German Regions	[327]	5.5
Multi-objective optimization of biogas systems producing hydrogen and electricity with solid oxide fuel cells	[289]	4.5
Optimal design and techno-economic assessment of low-carbon hydrogen supply pathways for a refueling station located in Shanghai	[328]	7.0
Optimization of PV-Grid Connected System Based Hydrogen Refueling Station	[329]	4.5
Performance evaluation of PV panels/wind turbines hybrid system for green hydrogen generation and storage: Energy, exergy, economic, and enviroeconomic	[330]	5.0

Title	ID	Quality Score
Portfolio of Wind-Photovoltaic-Loads Toward Green Hydrogen Development	[331]	5.5
Potential and Economic Analysis of Solar-to-Hydrogen Production in the Sultanate of Oman	[332]	6.5
Power-to-hydrogen pathway in the transport sector: How to assure the economic sustainability of solar powered refueling stations	[333]	6.5
Prospects of green hydrogen in Poland: A techno-economic analysis using a Monte Carlo approach	[149]	8.5
Recognizing the role of uncertainties in the transition to renewable hydrogen	[175]	6.5
Renewable hydrogen production: A techno-economic comparison of photoelectrochemical cells and photovoltaic-electrolysis	[334]	7.0
Roadmap to hybrid offshore system with hydrogen and power co-generation	[335]	7.5
Sizing, Optimization, and Financial Analysis of a Green Hydrogen Refueling Station in Remote Regions	[336]	5.0
Solar electricity storage through green hydrogen production: A case study	[337]	4.5
Solar PV and Wind Powered Green Hydrogen Production Cost for Selected Locations	[338]	4.0
Stochastic techno-economic analysis of power-to-gas technology for synthetic natural gas production based on renewable H2 cost and CO2 tax credit	[339]	7.0
Sustainability of hydrogen refuelling stations for trains using electrolysers	[163]	8.0

Title	**ID**	**Quality Score**
Technical, economic and environmental issues related to electrolysers capacity targets according to the Italian Hydrogen Strategy: A critical analysis	[340]	6.0
Technical, economic, carbon footprint assessment, and prioritizing stations for hydrogen production using wind energy: A case study	[341]	6.5
Techno economic feasibility study on hydrogen production using concentrating solar thermal technology in India	[342]	6.0
Techno-economic analysis and Monte Carlo simulation for green hydrogen production using offshore wind power plant	[343]	7.0
Techno-economic analysis and Monte Carlo simulation of green hydrogen production technology through various water electrolysis technologies	[166]	7.5
Techno-economic analysis and optimization of a novel hybrid solar-wind-bioethanol hydrogen production system via membrane reactor	[344]	5.5
Techno-economic analysis of current and emerging electrolysis technologies for green hydrogen production	[345]	6.5
Techno-economic analysis of green hydrogen ferries with a floating photovoltaic based marine fueling station	[346]	5.0
Techno-economic analysis of H2 energy storage system based on renewable energy certificate	[347]	7.5
Techno-economic Analysis of Hydrogen Electrolysis from Off-Grid Stand-Alone Photovoltaics Incorporating Uncertainty Analysis	[171]	7.5
Techno-economic analysis of hydrogen production electrically coupled to a hybrid desalination process	[348]	6.5
Techno-Economic Analysis of Low Carbon Hydrogen Production from Offshore Wind Using Battolyser Technology	[349]	5.0

Title	ID	Quality Score
Techno-economic assessment of clean hydrogen production and storage using hybrid renewable energy system of PV/Wind under different climatic conditions	[350]	5.5
Techno-economic assessment of green hydrogen valley providing multiple end-users	[351]	4.5
Techno-economic assessment of hydrogen pipe storage in decommissioned wellbores sourced from surplus renewable electricity	[352]	7.5
Techno-Economic Assessment of Hydrogen Production from vRE in Morocco Case Study: Laayoune, Ouarzazate, Midelt	[353]	5.0
Techno-economic assessment of hydrogen refueling station: A case study in Croatia	[354]	7.5
Techno-economic assessment of renewable hydrogen production and the influence of grid participation	[355]	7.0
Techno-economic evaluation of a grid-connected PV-trigeneration-hydrogen production hybrid system on a university campus	[356]	6.5
Techno-economic evaluation of medium scale power to hydrogen to combined heat and power generation systems	[357]	6.5
Techno-economic feasibility evaluation of a standalone solar-powered alkaline water electrolyzer considering the influence of battery energy storage system: A Korean case study	[358]	7.5
The cost of production and storage of renewable hydrogen in South Africa and transport to Japan and EU up to 2050 under different scenarios	[359]	5.0
The scheduling of alkaline water electrolysis for hydrogen production using hybrid energy sources	[360]	5.5
Thermodynamic and economic analyses of hydrogen production system using high temperature solid oxide electrolyzer integrated with parabolic trough collector	[361]	7.0

Title	ID	Quality Score
Thermoeconomic analysis of a solar-driven hydrogen production system with proton exchange membrane water electrolysis unit	[347]	5.0
True Cost of Solar Hydrogen	[209]	5.0
Wind energy utilization for hydrogen production in an underdeveloped country: An economic investigation	[303]	6.0
Wind resource assessment and techno-economic analysis of wind energy and green hydrogen production in the Republic of Djibouti	[362]	6.5

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