Assessing Energy Generation Technologies with Comprehensive Model Based on SQuaRE Standard

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***Abstract*—This study assesses energy generation technologies using a comprehensive model to support decision-making in energy project planning. We evaluated 11 energy generation technologies based on economic, environmental, and social metrics. Using the SQuaRE standard as a reference, we defined five distinct objectives, each of which was assigned a score to compare the technologies across five different scenarios. Each scenario addresses distinctive stakeholder interests. This approach provides a comprehensive view of each technology, enabling both broad and specific comparisons among them. Our results indicate that, in a general assessment, rooftop solar PV technology received the highest average score among the evaluated options, followed by small hydropower and offshore wind turbines; however, in a scenario where reliability is the most important factor, nuclear power ranked first among all technologies. Overall, this assessment reveals that renewable energy sources are rated more favorably than non-renewable ones, reflecting a global shift towards renewable solutions and acknowledgment of their potential benefits.**

***Keywords*—assessment, evaluation model, energy generation technologies, SQuaRE standard, decision-making, social impact, Sustainable Development Goals (SDG), smart grids, sustainable development**

I. Introduction

Energy project planning has traditionally been approached as an investment decision, where the lowest financial cost is reasonably sought. This is typically considered within a financial analysis framework that includes a cost model summarizing the economic needs of the system [1]. However, in the context of sustainable development and given the heterogeneous nature of energy sources, comprehensive planning must address various multidimensional aspects through a broad analysis that encompasses technical, economic, environmental, and social factors, as well as the participation of diverse stakeholders [2]. It is essential to acknowledge that some of these criteria may be in conflict. For instance, renewable technologies such as solar photovoltaics and wind turbines effectively reduce greenhouse gas emissions and promote environmental sustainability. However, they generally have lower reliability than traditional energy sources, making their energy output more dependent on weather conditions [3]. Conversely, nuclear power provides high reliability and a consistent energy supply but faces social challenges related to safety concerns and radioactive waste [4]. Consequently, planning should aim for a balanced or compromise approach among these criteria [5]. It is essential to perform a comprehensive assessment to identify the energy technology or technologies that best represent the social impact and the interests of the decision-makers [6].

Previous studies in energy power planning have produced numerous methodologies, revealing various approaches and strategies within the field. Different metrics and techniques have been utilized, underscoring the complex and multifaceted nature of energy power planning. This fragmentation emphasizes the need for a more systematic and unified approach, which could alleviate the challenges faced by decision-makers and yield more efficient and effective outcomes.

This study introduces a comprehensive model organized following the SQuaRE (Software Quality Requirements and Evaluation) standard. This model is specifically designed to help decision-makers effectively identify the most suitable energy technologies. Our approach emphasizes the importance of a balanced assessment, considering economic, environmental, and social criteria, which are critical factors in determining the sustainability and viability of energy solutions.

To develop this model, we systematically gathered and utilized a variety of metrics from established literature on energy technologies. These metrics were divided into five objectives following the SQuaRE standard, each reflecting different aspects of performance and impact. Furthermore, we evaluated eleven energy technologies, assessing their relative strengths and weaknesses in alignment with the identified objectives. This provides a robust framework for decision-making and enhances our understanding of how various energy technologies can contribute to sustainable development.

II. Background

Utilizing multidimensional metrics that encompass various backgrounds is essential to achieve a comprehensive perspective and a thorough framework for effective decision-making. The existing literature employs diverse metrics to evaluate energy technologies, with a particular emphasis on economic and environmental aspects, as these are the primary concerns of stakeholders involved in energy project planning. Nonetheless, social metrics hold significant importance as they address the problems faced by communities or end-users, which in turn impact the project's feasibility. Consequently, this study proposed the inclusion of social metrics alongside economic and environmental ones. Conversely, prior research has often employed metrics to evaluate a limited range of technologies or focused solely on renewable energy sources, thereby narrowing the assessment of energy technologies. Therefore, our study combined metrics and values from multiple studies to compare 11 different generation technologies, as outlined in Section III.

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The following metrics are selected in this study based on their applicability, impact in previous studies, data availability, and relation to the SQuaRE standard model for assessing energy generation technologies.

A. Economic Cost

When planning an energy project, assessing short-, medium-, and long-term costs is essential to avoid compromising economic interests. This helps compare costs of options and determine economic viability. Key characteristics like capacity and energy type influence construction, asset replacement, and operational expenses. Access to capital is crucial for electrification efforts [7, 8]. A widely used measure is the Levelized Cost of Energy (LCOE), which compares the costs of various energy generation technologies. It shows the average cost per unit of electricity (in USD/MWh) over a project's lifetime, factoring in capital, operating, maintenance, fuel costs, and expected production. LCOE standardizes cost-effectiveness comparisons, aiding policymakers and investors in making informed decisions. The average LCOE of selected technologies is displayed in Table 1.

Table 1. Average LCOE of each technology [9]

LCOE (2023 USD/MWh)		
PV	Rooftop	203
	Utility	60
Wind	Onshore	50
	Offshore	106
Hydropower [10]	Small	74
	Large	68
Coal	With CCS[1]	130
	Without CCS	118
Gas	With CCS[2]	92
	Without CCS	77
Nuclear		182

[1] There is an average increase of $12/MW by using CCS [11].
[2] There is an average increase of $15/MW by using CCS [11].

B. Greenhouse Emissions

Reducing greenhouse gas emissions is vital for sustainable development and combating climate change. When planning energy projects, assessing their environmental impact is essential to meet sustainability goals. By incorporating emission factors into the planning process, decision-makers can prioritize cleaner technologies and minimize negative environmental effects. While non-renewable energy is commonly associated with emissions, renewable sources can also produce emissions during construction and deployment. Table 2 details selected technologies' average life cycle greenhouse emissions [12].

Table 2. Life cycle greenhouse emissions of each technology [12]

Life cycle greenhouse emissions (gCO_2/kWh)		
PV	Rooftop	41
	Utility	48
Wind	Onshore	11
	Offshore	12
Hydropower [13]	Small	11
	Large[1]	150
Coal	With CCS	220
	Without CCS	820
Gas	With CCS	170
	Without CCS	490
Nuclear		12

[1] Includes biogenic emissions from reservoirs and emissions related to transport and infrastructure, which are assumed to occur over thousands of kilometers for this kind of technology [13].

C. Environmental Impact

Implementing an energy project involves assessing its environmental footprint, particularly water usage in manufacturing and operations. This demand can challenge local communities and ecosystems with limited water resources. Thus, evaluating water availability and impacts on local resources is essential for sustainability. Table 3 shows the average water usage for each selected technology, including manufacturing and operation.

Table 3. Water usage of each technology [13]

Water usage (L/kWh)		
PV	Rooftop	0.58
	Utility	0.63
Wind	Onshore	0.16
	Offshore	0.18
Hydropower	Small	0.039
	Large	0.37
Coal	With CCS	5.1
	Without CCS	2.9
Gas	With CCS	2.0
	Without CCS	1.2
Nuclear		2.4

D. Public Health

Renewable Energy Sources (RES) significantly reduce air pollution compared to fossil fuels, which emit harmful pollutants linked to respiratory diseases [14, 15]. Wind, solar, and hydroelectric power produce low air pollutants, resulting in cleaner air and improved respiratory health. However, the extraction and transportation of materials for RES do contribute to toxic emissions that need consideration. The toxicity of air pollutants can be categorized into carcinogenic and non-carcinogenic, with comparative toxic units (CTUh) used to estimate the impact on human morbidity [13]. Table 4 illustrates the toxicity potential of each technology.

Table 4. Non-carcinogenic and Carcinogenic toxicity potential of each technology [13]

Toxicity potential ($CTUh/TWh$)			
Technology		Non-carcinogenic	Carcinogenic
PV	Rooftop	13.8	1.6
	Utility	7.83	4.1
Wind	Onshore	2.98	6.6
	Offshore	3.17	5.5
Hydropower	Small	1.39	0.35
	Large	21.7	2.6
Coal	With CCS	166	10
	Without CCS	114	7.3
Gas	With CCS	13.0	1.7
	Without CCS	7.49	1.3
Nuclear		5.5	0.51

E. Job Generation

Energy projects significantly boost job creation and economic development by generating direct jobs in manufacturing, installation, and maintenance, as well as indirect jobs throughout the supply chain and local economy [16]. Direct job rates are measurable via survey analysis. In contrast, indirect jobs are harder to quantify due to sector interdependencies and the complexities of estimating total impacts over each technology's life cycle [17].

In this study, we use each technology's average jobs generated per unit of energy. Manufacturing, Construction, and Installation (MCI) jobs are usually short-term positions required during a project's initial phase, measured in job-years per MW, while operation and maintenance (O&M) roles are ongoing throughout the project's lifespan, measured in jobs per MW [18]. Table 5 displays the average job generation for each selected technology.

Table 5. Jobs in manufacturing, construction, installation, operation, and maintenance generated by each technology [18]

Jobs generated		MCI (Jobs-years/MW)	O&M (Jobs/MW)
PV [19]	Rooftop	32.7	1.4
	Utility	19.7	0.7
Wind	Onshore	7.9	0.3
	Offshore	23.6	0.2
Hydropower	Small	27.25	0.5
	Large	10.9	0.2
Coal	With CCS[a]	16.5	0.14
	Without CCS[a]	16.5	0.14
Gas	With CCS[1]	4.7	0.14
	Without CCS[a]	4.7	0.14
Nuclear		13.1	0.6

[1] No data available distinguishing between utilizing CCS and not.

F. Population Acceptance

Community acceptance is crucial for the success of an energy project. Land use, visual impact, noise, and health concerns significantly shape public perception [20]. Social acceptance is complex, involving socio-political, community, and market dimensions that interact in conflicting ways [21, 22]. Researchers employ surveys, focus groups, and interviews to gauge public attitudes and support, yielding insights that build trust, address concerns, and enhance acceptance of renewable energy projects [23, 24].

A survey conducted across various European countries asks respondents how much energy they believe should be generated from each energy source [4]. Based on this information, we assigned a value ranging from 0 to 1 to each amount of energy (0=None, 0.25=Small, 0.5=Medium, 0.75=Large, 1=Very Large) and calculated a unique value for each selected technology using a weighted average method, as illustrated in Table 6.

Table 6. Population acceptance of each technology

Population acceptance		
PV	Rooftop[1]	0.78
	Utility[1]	0.78
Wind	Onshore[1]	0.74
	Offshore[1]	0.74
Hydropower	Small[1]	0.71
	Large[1]	0.71
Coal	With CCS[1]	0.26
	Without CCS[1]	0.26
Gas	With CCS[1]	0.47
	Without CCS[1]	0.47
Nuclear		0.28

[1] Population acceptance is based only on energy source type. Technologies using the same energy source have the same value

G. Reliability

The capacity factor of an energy generation technology is the ratio of its actual output to its maximum output over a specific period. It is an important measure of reliability, as a higher capacity factor indicates that a technology is at its full potential more consistently. Renewable sources like wind and solar have lower factors due to weather dependence, whereas non-renewable sources like natural gas or nuclear maintain higher factors due to continuous power generation. Table 7 lists the average capacity factor of each selected technology.

Table 7. Capacity factor of each technology [25]

Capacity factor (%)		
PV	Rooftop	25
	Utility	25
Wind [10]	Onshore	36
	Offshore	41
Hydropower	Small	52
	Large	53
Coal	With CCS	50
	Without CCS	50
Gas	With CCS	55
	Without CCS	55
Nuclear		93

H. Construction Time

The duration required to implement an energy project plays a crucial role. In certain instances, the primary motivating factor for initiating a new energy project is its deployment speed. This is particularly relevant in markets or regions that are rapidly evolving or need fast energy solutions. Consequently, technologies that can be constructed and operationalized quickly become highly sought after. Table 8 illustrates the average construction time associated with each energy technology.

Table 8. Average construction time of each technology [26, 27]

Construction time (Months)		
PV	Rooftop	1.7
	Utility	10.3
Wind	Onshore	12
	Offshore	12
Hydropower	Small [28]	14
	Large	48
Coal	With CCS[a]	66
	Without CCS	55
Gas	With CCS[b]	44
	Without CCS	41
Nuclear		60

I. Land Usage

Table 9. Land usage by each technology [13]

Land usage ($m^2 - year/MWh$)		
PV	Rooftop	10.36
	Utility	18.65
Wind	Onshore	0.94
	Offshore	0.98
Hydropower	Small	41.95
	Large	15.20
Coal	With CCS	28.35
	Without CCS	20.15
Gas	With CCS	2.04
	Without CCS	1.43
Nuclear		0.72

When planning the deployment of an energy project, it is crucial to consider land use. Areas with limited land may face challenges implementing large-scale projects or technologies that need substantial space. Land use involves not only the area necessary for the installation and operation of each technology but also the land required for resource extraction, which is essential for manufacturing these technologies. This multifaceted consideration is vital for ensuring the project's feasibility and sustainability in a region. Land usage is expressed in $m^2 - year/MWh$, which allows consideration of land usage in relation to the life expectancy of a technology.

In other words, two technologies occupying the same area per kW (m^2/kW) will have different land usage values if their life expectancy is different. Table 9 shows the average land usage for each technology in Europe.

III. Proposed Method

We present a model, shown in Fig. 1, designed to assist decision-makers in planning energy projects by identifying suitable energy technologies. This structured framework integrates various factors to ensure chosen technologies align with key economic, environmental, and social objectives, adapted from the SQuaRE standard. The process begins by assessing metrics for each technology and comparing their performance across five key objectives. Ultimately, the model produces an overall performance score to facilitate informed decisions for selecting renewable energy technologies.

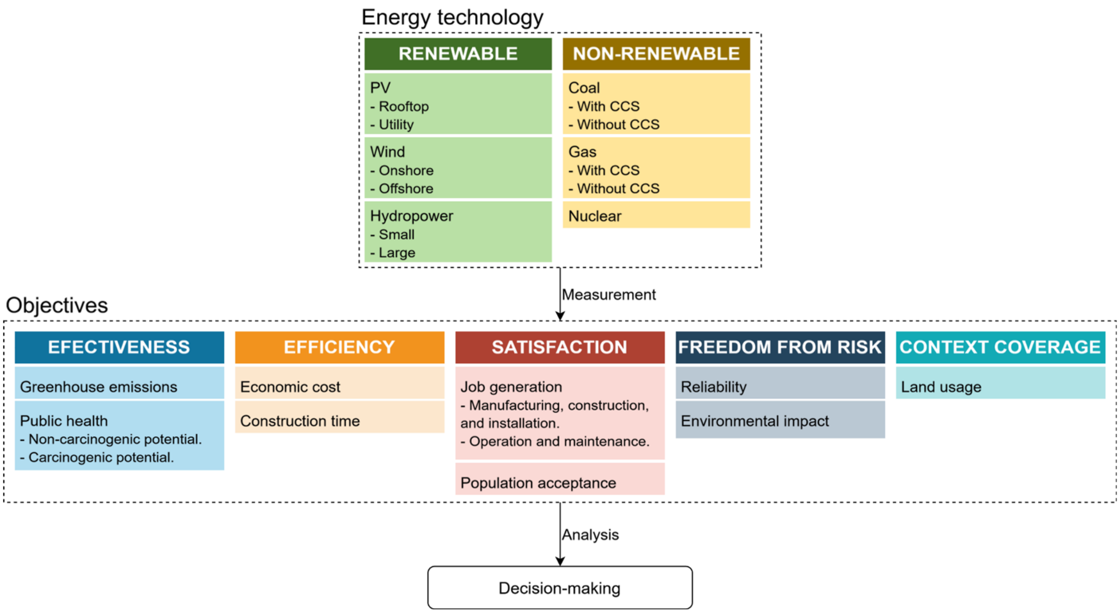

Fig. 1. Proposed general model.

A. Metrics

A comprehensive evaluation of energy technologies requires economic, environmental, and social metrics. However, analyzing these metrics can be challenging, particularly when they present conflicting information. To address this complexity, we employ the SQuaRE standard, a framework originally developed for software assessment. This standard is a valuable tool that simplifies understanding how each energy technology performs across various dimensions.

In our analysis, we identified five distinct dimensions that we consider objectives for this study. Each objective comprises all associated metrics described previously in section 2, which we normalize to facilitate effective comparisons among the objectives. This process involves transforming each metric into a standardized value between 0 and 1, which we refer to as a score. Metrics with positive connotations—where higher values are better, like Job Generation or Reliability—are standardized using the Eq. (1). Meanwhile, metrics carrying negative connotations—where lower values are better, like Greenhouse emissions or Economic cost— are standardized and inverted using Eq. (2). This facilitates the overall evaluation process as achieving a high score in a metric always indicates better performance.

$$s = (x_i - x_{min})/(x_{max} - x_{min}) \quad (1)$$

$$s = 1 - (x_i - x_{min})/(x_{max} - x_{min}) \quad (2)$$

where n is the metric score for the technology i. x_i is the metric value for the technology i. x_{min} is the metric minimum value among all technologies. x_{max} is the metric maximum value among all technologies.

B. Power Technologies

This study comprehensively compares 11 energy generation technologies, spanning both renewable and non-renewable sources. Our goal is to provide decision-makers with a comprehensive understanding of these technologies, enabling them to make informed choices within the energy landscape.

1) Renewable energy technologies

The most prevalent forms of renewable energy sources (RES) include solar, wind, and hydro energy, each offering unique advantages and applications. We selected two distinct technologies from each category to compare comprehensively.

For solar energy, we focus on crystalline silicon solar photovoltaics (PV), which are versatile enough to be employed in both rooftop installations for residential use and large-scale utility projects that contribute significantly to energy grids.

For wind energy, our selection includes two types of turbines: onshore wind turbines, which are installed on land and often harness wind from coastal or elevated regions, and offshore wind turbines, located in marine environments where wind speeds are typically higher and more consistent, thereby maximizing energy production.

Regarding hydropower, we have categorized the technology into two segments: small hydropower plants, which have an average capacity of 10 MW, and large hydropower facilities, with an average capacity of 300 MW. This distinction helps clarify how scale affects energy generation in the hydropower sector.

2) Non-renewable energy technologies

We focused on three primary energy sources: coal, natural gas, and nuclear.

For coal, we selected the traditional steam turbine system that uses pulverized coal (PC), which is widely adopted in the industry. Additionally, we considered two versions of this technology: one incorporating carbon capture and storage (CCS) to reduce greenhouse gas emissions, and the other without it.

Regarding natural gas, we selected combined cycle technology, which is known for its high efficiency. Similar to our coal analysis, we evaluated a variant with CCS and another that operates without it.

For nuclear energy, we focused on the average water reactor, which represents a standard in nuclear power generation. This comprehensive approach enables us to understand better the characteristics and implications of each energy source in our study.

C. SQuaRE standard

The SQuaRE standard (ISO 25000) defines and evaluates software quality requirements. It provides a structured approach for assessing quality in key areas, including functionality, reliability, usability, efficiency, maintainability, and portability. This standard helps organizations establish clear, measurable quality criteria aligned with user needs, includes predefined metrics for evaluating compliance, and identifies areas for improvement. Its consistent approach facilitates comparative analysis and benchmarking, supporting strategic resource allocation and project management decisions. This work incorporates multiple criteria categorized into five key objectives: effectiveness, efficiency, satisfaction, freedom from risk, and context coverage [29], providing a comprehensive framework for systematically assessing decision-making.

D. Objectives

1) Effectiveness

In the SQuaRE standard, this objective measures how well the software achieves its intended purpose. It involves assessing whether the software enables users to achieve their goals and complete their tasks accurately and efficiently

To adjust this objective, we recognized that rising concerns about climate change are making the planning phase of energy projects increasingly important. Energy generation is closely tied to the United Nations' Sustainable Development Goals (SDGs). Goal 7 ensures access to affordable, clean energy, while Goal 13 urges action against climate change. Thus, each energy initiative must align with these global objectives. Effectiveness indicates how well an energy project satisfies energy demands while supporting sustainability, so metrics related to energy access and greenhouse emissions are associated with this objective.

2) Efficiency

In the SQuaRE standard, this objective refers to the software's performance in terms of resource usage. It involves evaluating whether the software provides the desired functionality while optimizing the use of resources, such as time, memory, and processing power.

In energy generation planning, we view efficiency as a comprehensive assessment of how effectively a plan or strategy achieves its desired results while optimizing the use of available resources. This process requires an in-depth analysis that contrasts the economic costs incurred with the benefits ultimately gained. Efficiency ensures that planning an energy project focuses on achieving the desired functionality and emphasizes maximizing value while minimizing waste.

Metrics represent the use of resources of a planning team, such as cost and implementation time, which are associated with this objective.

3) Satisfaction

In the SQuaRE standard, this objective assesses users' perceptions of the software. It involves assessing user satisfaction regarding usability, comfort, and overall experience with the software.

In energy generation planning, we believe Satisfaction indicates how much the community is pleased with the improvements, emphasizing their experiences and perceived benefits. Energy projects, especially large installations, can impact local communities and landscapes. For instance, properties near these installations may lose value due to visual, noise, or environmental concerns. Conversely, such projects can boost local economies by generating new business opportunities, including jobs in construction and maintenance for renewable energy infrastructure, as well as roles in research and manufacturing.

Metrics related to social acceptance and social development are closely tied to this objective.

4) Freedom from risk

In the SQuaRE standard, this objective focuses on ensuring that the software does not cause harm to users, data, or the environment. It involves evaluating how well the software handles errors, security issues, and other risks.

In energy generation planning, Freedom from risk requires evaluating how well energy projects ensure that advancements in energy production do not introduce new risks. For instance, the shift to renewable energy presents an opportunity to reduce greenhouse gas emissions, but its inherent intermittency can lead to supply fluctuations, raising concerns about energy system reliability.

Metrics related to energy risk and ecosystem impacts are associated with this objective.

5) Context coverage

In the SQuaRE standard, this objective assesses how comprehensively the software addresses the needs and conditions of different users and contexts.

In energy generation planning, Context coverage assesses how easily an energy project can be developed across various regions or locations. In this regard, the space required to deploy a technology can provide insight into the feasibility of constructing it.

Metrics related to land usage, location access, and regulatory impediments are associated with this objective.

IV. Results and Discussion

A. Effectiveness Score

Life cycle emissions and toxicity values were normalized and inverted, as shown in Fig. 2.

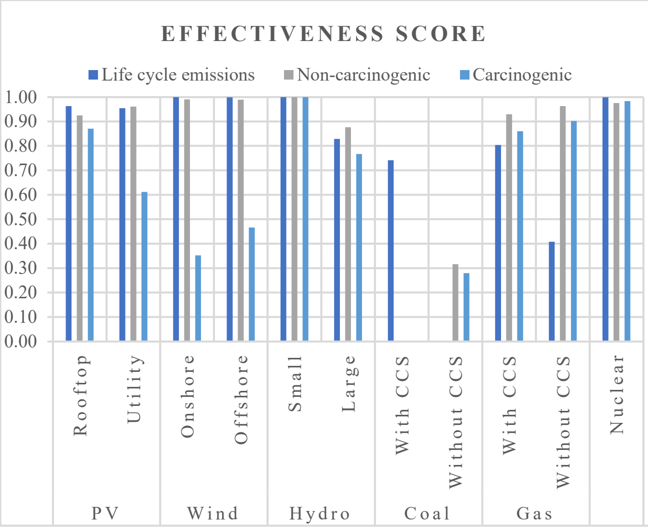

Fig. 2. Effectiveness scores by each technology.

Results indicate that coal and gas have the poorest performance regarding life cycle emissions. However, the implementation of CCS significantly mitigates these emissions, thereby enhancing their overall environmental performance.

Regarding toxicity potential, chromium and arsenic in the manufacturing processes are the main contributors to the lower scores observed [13].

On the other hand, wind energy technologies demonstrate high scores in life cycle emissions and non-carcinogenic toxicity. However, the potential carcinogenic risk associated with the materials used in construction lowers their toxicity ratings, resulting in even lower scores than those of gas technology.

Nuclear technology, in contrast, consistently ranks highly across all three categories—life cycle emissions, non-carcinogenic toxicity, and carcinogenic potential—indicating a more favorable overall environmental footprint.

B. *Efficiency Score*

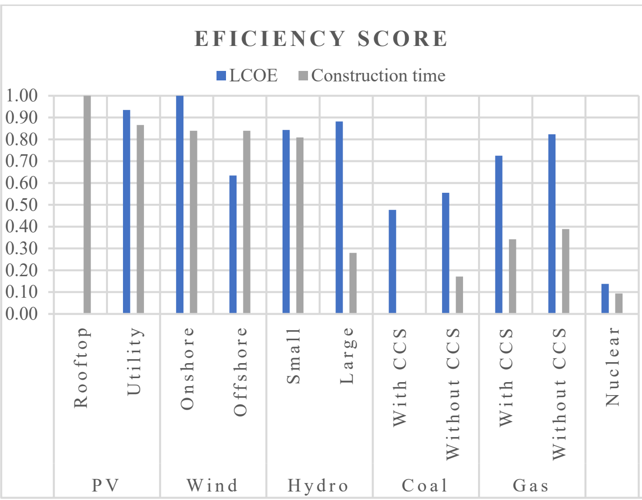

Fig. 3. Efficiency scores by each technology.

The LCOE and construction time values were normalized. The results are shown in Fig. 3. Solar PV rooftop systems have the lowest LCOE lowest LCOE score but the highest construction time score, as they serve smaller capacity needs for quicker implementations. In contrast, onshore wind turbines have the highest LCOE, followed by utility-scale solar PV. Among non-renewable technologies, natural gas without CCS achieved the best LCOE, slightly outperforming offshore wind and slightly behind small hydropower. CCS incorporation improves life cycle emissions scores but increases LCOE and construction times due to the additional materials and labor required.

Nuclear energy technology ranked the lowest across all assessed technologies. This is primarily due to its significantly high capital and operational costs, which outweigh the energy generated, as well as the substantial labor and complexity involved their construction.

C. *Satisfaction Score*

Job generation and population acceptance values were normalized, as shown in Fig. 4.

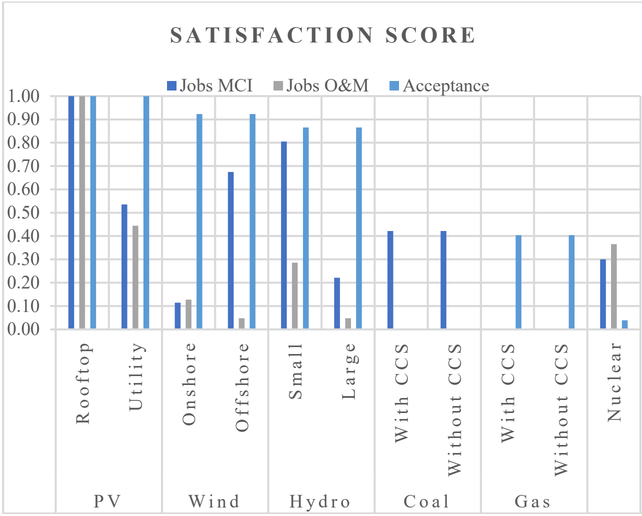

Fig. 4. Satisfaction scores by each technology.

Solar PV rooftop systems have the highest ratings for both types of Job creation and Public acceptance among all the evaluated technologies. This score can be attributed to the small-scale nature of solar PV rooftops, which leads to a more favorable jobs-per-MW ratio. Additionally, this factor significantly affects the capital and operational costs associated with this technology, as analyzed previously.

In a broader comparison, renewable energy technologies consistently achieve much higher acceptance scores than their non-renewable counterparts, highlighting a growing public preference for sustainable energy solutions.

When examining job generation specifically, onshore wind turbines rank lowest among the selected technologies, which contrasts sharply with the situation for offshore wind turbines. The latter typically requires a larger installation and an ongoing maintenance workforce, contributing to their higher job generation capacity.

While natural gas is responsible for providing the fewest jobs compared to other technologies, it does enjoy greater public acceptance than coal and nuclear energy. This difference is largely attributed to the widespread environmental concerns associated with coal and safety issues linked to nuclear power, which have declined their popularity.

D. *Freedom from Risk Score*

The Capacity factor and water usage values were normalized; only the latter was inverted. The results are shown in Fig. 5.

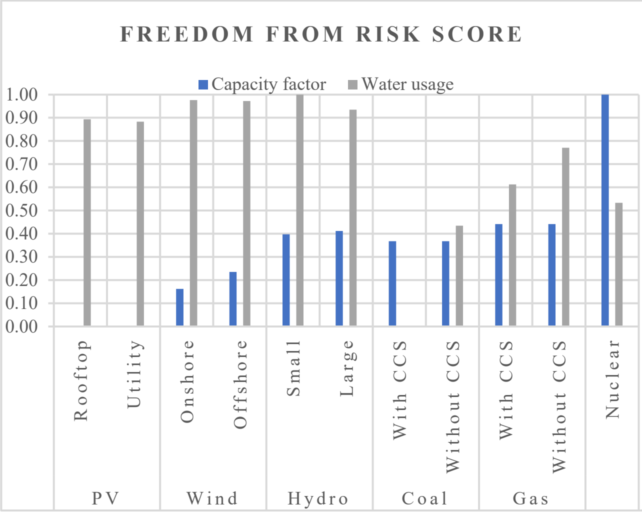

Fig. 5. Freedom from risk scores by each technology.

Nuclear energy stands out with the highest capacity factor, indicating it is the most reliable form of energy generation among the selected technologies. In contrast, solar PV and wind power exhibit the lowest capacity factors, primarily due to the intermittent nature of their energy sources, sunlight and wind, which can vary significantly over time.

Hydropower's capacity factor is comparable to that of conventional fossil fuels like coal and natural gas, providing a consistent energy output.

When it comes to water usage, renewable energy technologies significantly outperform their non-renewable counterparts. This difference, combined with their lower greenhouse gas emissions, highlights the reduced environmental impact of renewable energy solutions compared to traditional fossil fuel technologies.

E. Context Coverage Score

The Capacity factor and Water usage values were normalized, with only the latter inverted, as shown in Fig. 6.

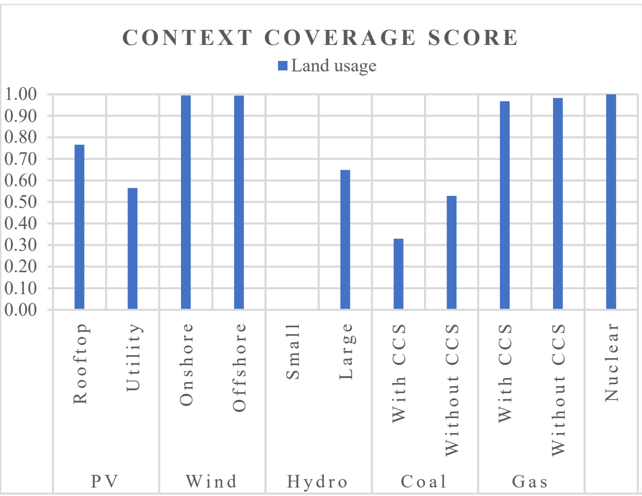

Fig. 6. Context coverage scores by each technology.

Nuclear energy ranks the highest among energy sources in terms of land usage, making it an attractive option for power generation. It is closely followed by wind energy and natural gas, both of which also demonstrate favorable land usage scores.

In contrast, hydropower tends to score lower in land usage because of the extensive reservoirs often required to harness water flow effectively. Similarly, coal energy has a diminished score, primarily due to the substantial land needed to extract the raw materials necessary for energy production.

Wind energy stands out with a high score largely because, for many onshore wind farms, the land beneath the turbines remains available for other uses, such as agriculture. This dual-use potential maximizes land productivity. Offshore turbines also have another useful aspect: while they occupy marine areas, they do not suppress other economic activities within those waters, such as fishing. Thus, wind energy harnesses natural resources efficiently and supports complementary land and sea uses.

F. Comparative Analysis

The results obtained for each metric highlight the various trade-offs that may occur when choosing a technology. It falls to the decision-maker to carefully evaluate the interests of stakeholders and weight each metric based on these considerations.

In this study, we present five distinct scenarios, each emphasizing different weighting to reflect the diverse priorities and interests of stakeholders. By varying the importance assigned to each metric, we aim to showcase how these differences can influence technology selection. The scenarios we explore are as follows:

- Average scenario: Each metric has the same importance.
- Cost scenario: LCOE is 3 times more important than other metrics.
- Health and pollution scenario: Effectiveness metrics are 3 times more important than other metrics.
- Social scenario: Satisfaction metrics are 3 times more important than other metrics.
- Reliability and context coverage: Capacity factor and context coverage metrics are 3 times more important than other metrics.

1) Average scenario

In this scenario each score is weighted equally, allowing for average calculations for each objective, as illustrated in Fig. 7.

Results indicate that small hydropower has the highest Effectiveness score, closely followed by nuclear energy. Both sources show significantly lower impacts on greenhouse gas emissions and public health compared to other energy options. Conversely, the remaining renewable technologies exhibit Effectiveness scores that align more closely with those of natural gas. Among all the energy sources assessed, coal has the lowest Effectiveness score, whether with or without CCS.

When evaluating Efficiency, renewable energy technologies outperform Nuclear and Coal. However, natural gas shows a competitive score of slightly above rooftop solar PV, and above large hydropower when using CCS.

In terms of Satisfaction, renewable energy sources have higher scores than non-renewable sources, with solar PV rooftop installations leading in this category. This is primarily due to the positive perception of renewable energy among the population compared to non-renewable alternatives.

Nuclear energy stands out for its score in Freedom from Risk, showing its reliability as an energy source. Gas, wind energy, and large hydropower all possess similar risk profiles, whereas coal falls behind with the lowest score in this area.

When examining Context Coverage for power generation, nuclear energy ranks the highest, followed closely by wind energy and natural gas. In contrast, hydropower receives a lower score due to the extensive reservoirs required for its operation. Coal's land usage score is further diminished due to the vast amount of land needed for extraction activities, highlighting the broader impact of different energy sources on land use.

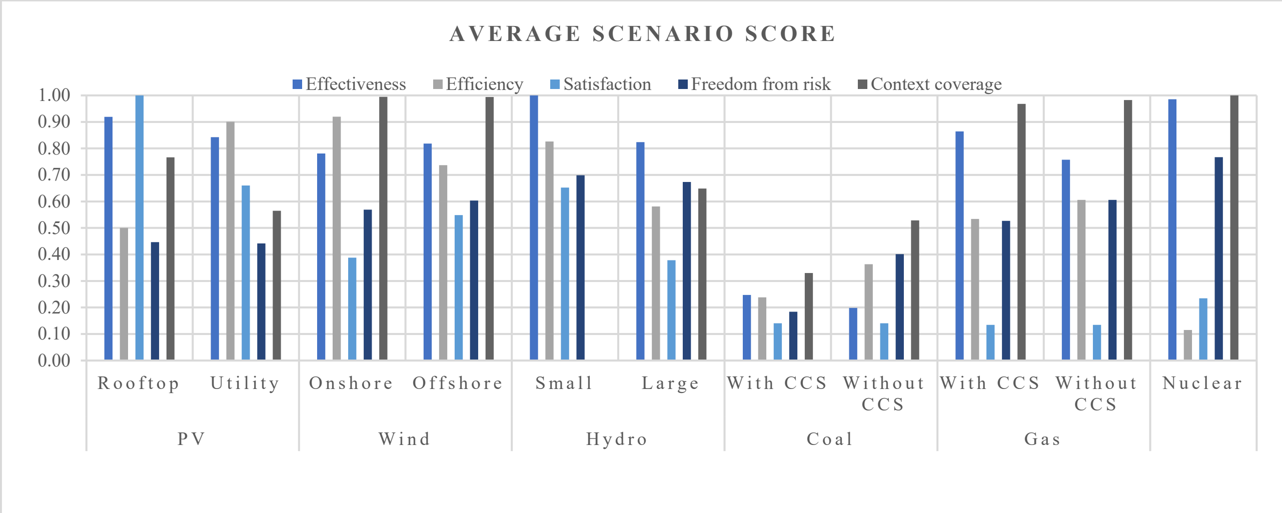

Fig. 7. Average scenario scores on each objective by each technology.

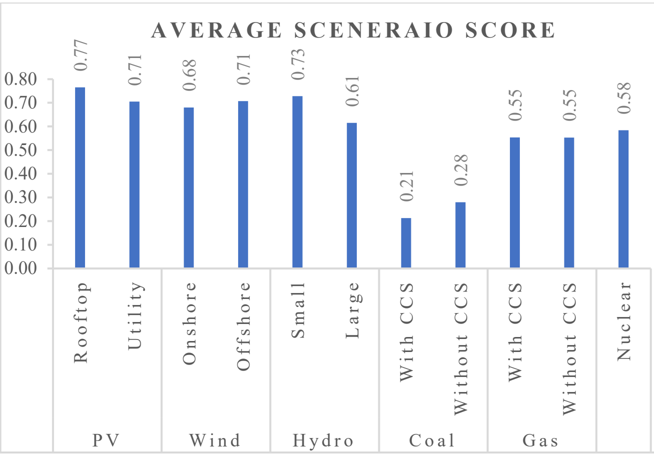

Fig. 8. Average scenario score of each technology.

In our analysis, we also calculated an overall score by treating each individual score equally, resulting in a unique score for each technology. Fig. 8 illustrates the findings.

Rooftop solar PV achieved the highest average score, mainly due to its effectiveness, followed by small hydropower. Offshore wind turbines and utility-scale solar PV tied at 0.71, while onshore wind scored 0.68. This ranking shows that renewable sources are increasingly favored over non-renewable ones, aligning with the global shift towards sustainability and highlighting the need to invest in renewable resources to combat climate change. Conversely, nuclear energy ranks highest among non-renewables. Despite concerns about high costs and societal acceptance, it offers reliable electricity generation with no carbon emissions, making it an attractive option for sustainable solutions. Therefore, while renewable options are prioritized, nuclear energy remains crucial in the energy landscape. Natural gas follows nuclear energy, irrespective of CCS use; here, CCS's effectiveness score is contrasted with efficiency and risk scores.

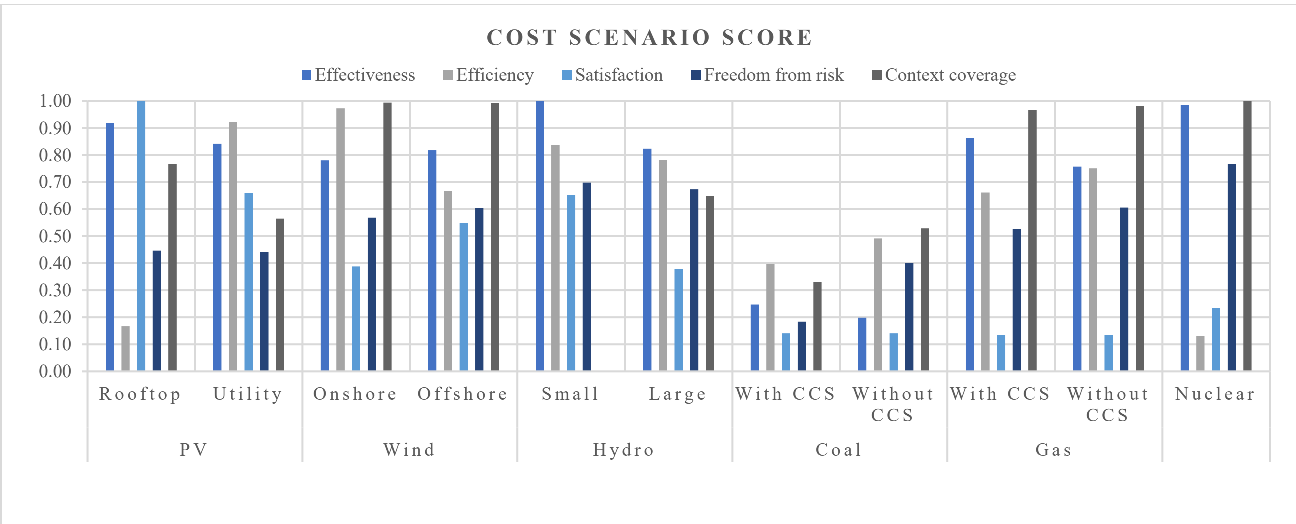

Fig. 9. Cost scenario scores on each objective by each technology.

2) *Cost scenario*

In this scenario, cost (LCOE) is three times more important than the other factors. It highlights a stakeholder perspective that emphasizes cost reduction above all other aspects of energy planning. Fig. 9 shows the score for each objective.

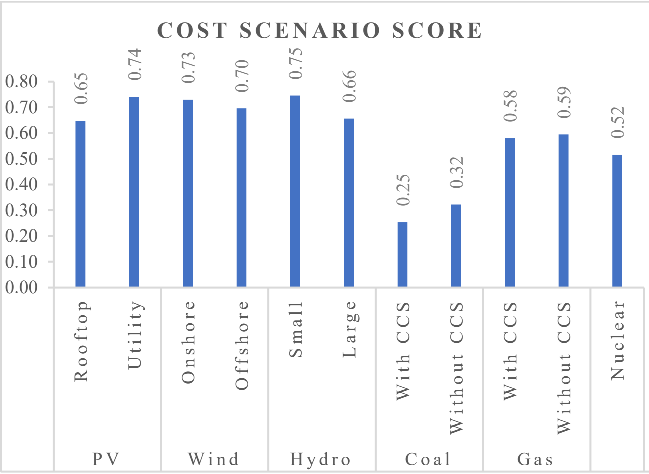

Fig. 10. Cost scenario score of each technology.

In comparison to the average scenario, only the Efficiency score was impacted since only the weight of the LCOE metric changed. The results indicate that PV rooftop, offshore wind, and nuclear power reduced the efficiency score, while other technologies increased it, particularly large hydropower and other non-renewable technologies.

The overall score result is shown in Fig. 10. Small hydropower achieved the highest score, followed by PV utility.

3) *Health and pollution scenario*

In this scenario, effectiveness metrics (life cycle emissions, and both carcinogenic and non-carcinogenic toxicity potential) are three times more important than other metrics. This highlights a stakeholder's interest in the carbon footprint and health impacts of energy planning. Fig. 11 shows the score for each objective.

In this scenario, as all effectiveness metrics increased their weight by the same amount, the effectiveness score and all objective scores remain the same compared to the average scenario. However, the overall score results differ as it is shown in Fig. 12.

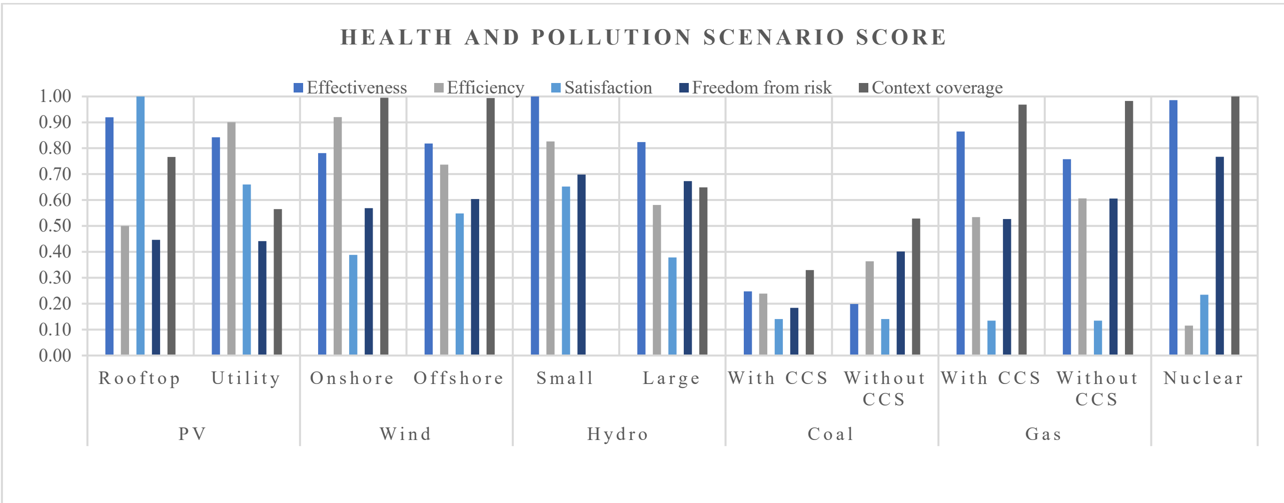

Fig. 11. Health and pollution scenario scores on each objective by each technology.

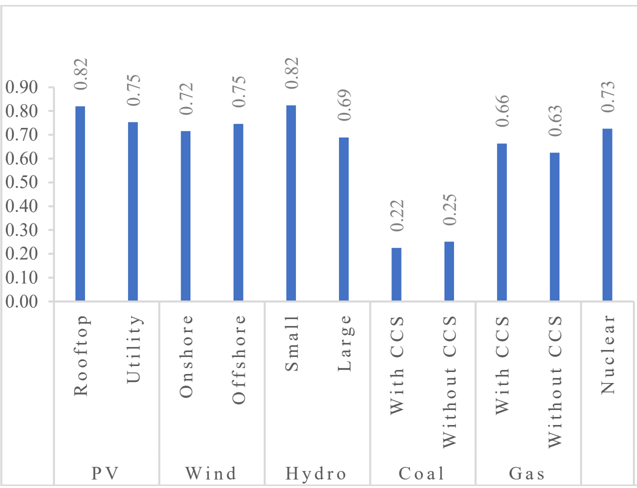

Fig. 12. Health and pollution scenario score of each technology.

In this scenario, all technologies except coal saw an increase in their overall scores compared to the average scenario. This was particularly notable for small hydropower, which tied for the highest score with PV rooftop. Additionally, nuclear power surpassed wind onshore and is only slightly behind PV utility and wind offshore.

4) *Social scenario*

In this scenario, satisfaction metrics, job generation and acceptance, are three times more important than other metrics. This highlights a stakeholder's interest in community economic development and the public reception of an energy project. Fig. 13 shows the score for each objective.

In this scenario, as all Satisfaction metrics increased their weight by the same amount, the Satisfaction score and all objective scores remain the same compared to the average scenario. However, the overall score results differ as shown in Fig. 14.

In this scenario, all technologies except PV rooftop experienced a decrease in their scores to varying degrees. The impact is most significant for non-renewable technologies. Results indicate that PV rooftop has the highest score, driven by substantial job creation and acceptance, followed by small hydropower and PV utility. In this scenario, all renewable technologies ranked above non-renewable options. Among the non-renewable technologies, nuclear power achieved the highest score.

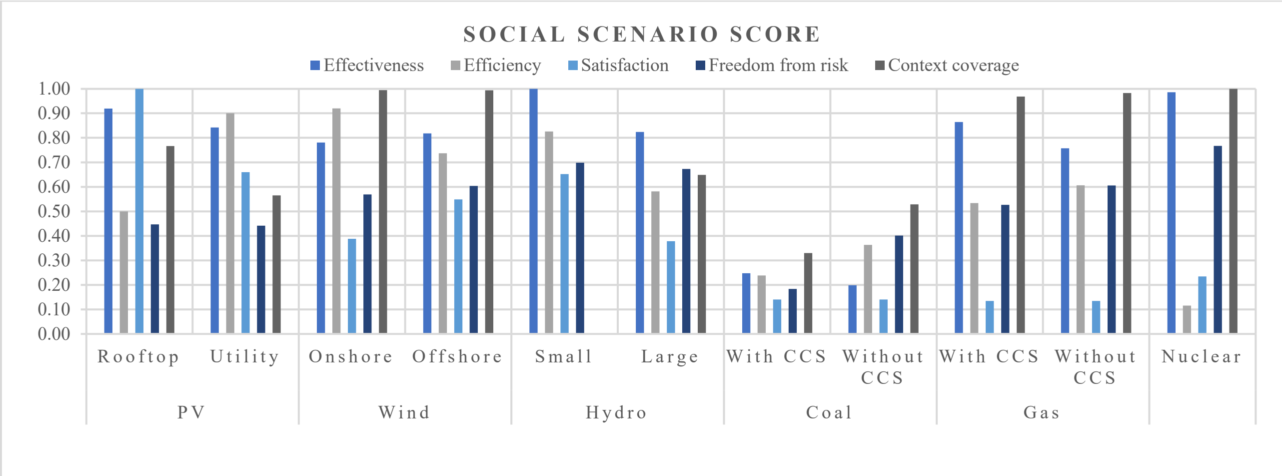

Fig. 13. Social scenario scores on each objective by each technology.

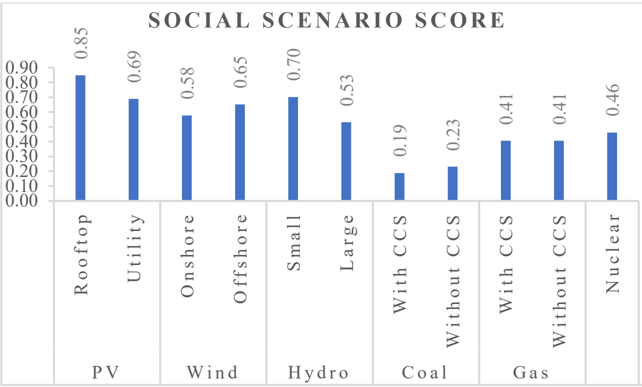

Fig. 14. Social scenario score of each technology.

5) Reliability and context coverage scenario

In this scenario, capacity factor and land usage are three times more important than other metrics. This highlights a stakeholder's interest in the stability and flexibility of the energy project. Fig. 15 shows the score for each objective.

In this particular scenario, the Freedom from Risk score exhibited a change when compared to the average scenario, while the scores for the other objectives remained unchanged. The results indicate that coal CCS technology, as well as nuclear energy, increased their Freedom from Risk score. Conversely, the other technologies, particularly PV and wind energy, experienced a decline in their scores.

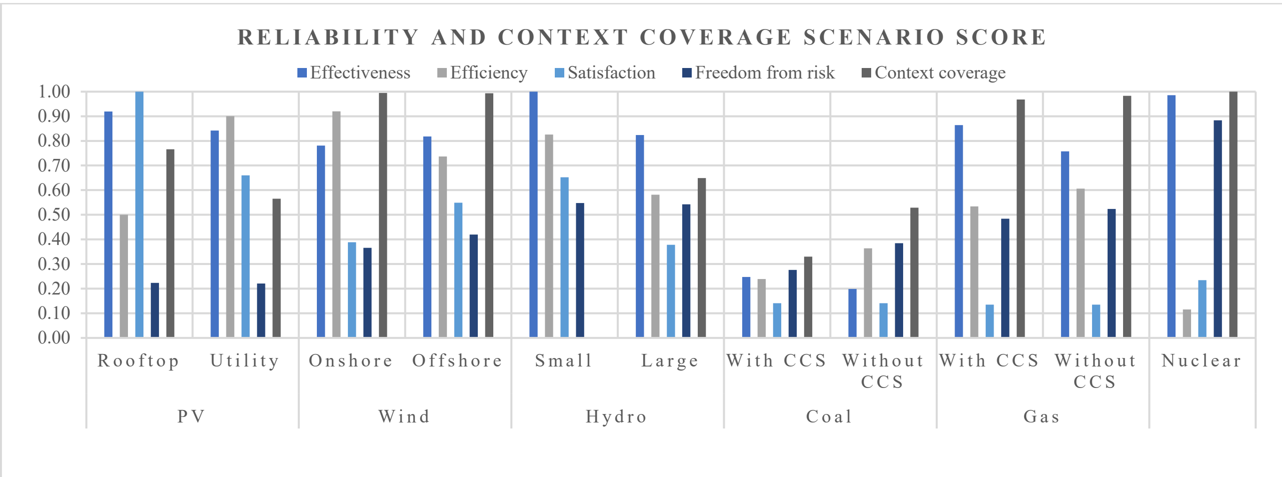

Fig. 15. Reliability and context coverage scenario scores on each objective by each technology.

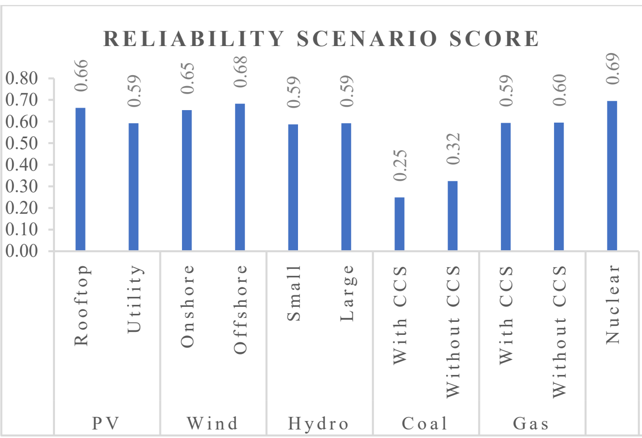

Fig. 16. Reliability and context coverage scenario score of each technology.

The overall score results, illustrated in Fig. 16, indicate a decline in scores for all renewable technologies. In contrast, all non-renewable technologies showed an increase in their scores compared to the average scenario. Notably, nuclear power achieved the highest score, followed closely by wind offshore and then PV rooftop systems.

6) Scenario analysis

The outcomes of the five scenarios underscore the crucial role of the decision-maker in the planning of an energy project, as well as the necessity to clearly identify project priorities. The varying combinations of weights assigned to different evaluation metrics significantly influence the assessment of energy technologies. This variation illustrates that selecting the most suitable solution is profoundly dependent on the specific context and requirements of the project at hand. Furthermore, the functionality of the model presented in this study effectively facilitates the comparison of all these scenarios, revealing the trade-offs associated with the chosen technologies and their implications for project planning.

V. CONCLUSION

In this study, we presented an assessment of energy technologies using a comprehensive model to aid in decision-making for planning energy projects. The results indicate that each technology has a distinct impact on the proposed objectives, making it difficult to determine the most effective technology. However, we provide a holistic perspective by considering economic, environmental, and social aspects, assigning a score to represent their overall performance.

Our analysis shows five different scenarios based on different stakeholders' perspectives.

Our analysis shows that small hydropower has the highest Effectiveness score, closely followed by nuclear energy. Both have lower impacts on greenhouse gas emissions and public health compared to other sources. The remaining renewable technologies' effectiveness scores align more closely with natural gas, while coal has the lowest effectiveness.

Regarding efficiency in the average scenario, renewable energy technologies rank ahead of Nuclear and Coal. Nevertheless, natural gas presents a competitive score that slightly surpasses rooftop solar PV and ranks higher than large hydropower when utilizing CCS. In contrast, in the cost scenario, onshore wind ranked first while PV rooftop drastically reduced its score, only ranking higher than nuclear energy.

In Satisfaction, renewable sources generally score higher, with solar PV rooftop installations leading.

Nuclear energy excels in freedom from risk, especially in the Reliability scenario, greatly surpassing all other technologies. Gas, wind, and large hydropower share similar risk profiles, while coal has the lowest.

In Context Coverage for power generation, nuclear power ranks highest, followed by wind energy and natural gas. Hydropower scores lower due to the large reservoirs needed, and coal's score drops because of the significant land required for extraction, demonstrating the varied impacts of energy sources on land use.

Based on the average scenario score, rooftop solar PV technology ranks the highest among all evaluated technologies, largely due to its effectiveness score. Small hydropower follows in second place, and Offshore wind turbines and utility-scale solar PV are tied for third, slightly ahead of onshore wind turbines.

In the cost scenario, small hydropower had the highest average score, while in the health and pollution scenario, PV rooftop and small hydropower scored the highest.

In the social scenario, PV rooftop and small hydropower ranked again above all other technologies.

In contrast, in the reliability scenario, nuclear power claimed the top spot, followed by wind, offshore, and then PV rooftop.

Overall, this assessment reveals a clear trend: renewable energy sources are rated more favorably than non-renewable ones, but it also highlights that non-renewable technologies, especially nuclear power, have an advantage in terms of reliability. Nonetheless, this aligns with the growing global momentum toward transitioning to renewable energy solutions, reflecting widespread recognition of their potential benefits. Through this analysis, we demonstrated that our proposed model can evaluate various aspects of energy generation technologies and support the decision-making process based on stakeholders' interests. This model is adaptable and can be modified as needed by the decision-maker.

VI. LIMITATIONS

The results of this study are based on data collected from multiple studies conducted worldwide. We used global average data to ensure a fair comparison among the selected technologies in a broad context and to demonstrate the general applicability of our proposed model in energy planning. However, when evaluating a specific region, it is essential to consider regional factors such as renewable energy potential, technology costs, construction timelines, and population acceptance. Incorporating these localized elements would produce results that are more accurate and relevant for that particular region than the generalized data provided in this study.

On the other hand, while the LCOE metric is suitable for a global technology evaluation, it may fall short in accounting for regional factors that raise technology costs, such as integration expenses, energy storage costs, and energy losses from excessive generation, particularly for renewable technologies. Therefore, including metrics like the levelized cost of storage (LCOS) and the levelized avoided cost of energy (LACE) can help address this limitation.

Moreover, we provide a detailed overview of the most widely used energy generation technologies at present. This array of technologies is intentionally varied and reflects a broad spectrum of relevance in the current energy sector. However, it's essential to highlight that there are significant energy generation methods, including geothermal, biomass, and hydrogen power, which are less commonly utilized. These technologies were excluded from this study mainly because there is a lack of comprehensive global data on certain crucial metrics. This absence of reliable information prevents us from making fair comparisons with the technologies we have selected for analysis.

Similarly, Supercritical/IGCC and other technologies were not included due to insufficient data comparability.

VII. FUTURE WORK

The values for each objective in this study are derived from global averages, highlighting the framework's applicability across various contexts. This versatile model can also incorporate local factors, enabling a more targeted approach to energy planning that considers regional specificities. Moreover, we encourage integrating new metrics that effectively evaluate the impact of resource availability and the political dynamics that influence energy accessibility in more specific contexts.

Conversely, evaluation is merely the initial application of this model. While most metrics measure power technologies by the amount of electricity produced, we suggest broadening the model's use to incorporate generation profiles for each technology. This adjustment will enhance the understanding of the variability in these technologies, particularly in the case of renewable energy sources.

Alternatively, other energy generation methods could be incorporated into the model. For instance, floating solar photovoltaic (PV) systems have become a scalable option for land-limited areas, allowing solar panels to be installed on reservoirs and water bodies. In wind energy, floating offshore turbines have expanded the potential to harness wind power in deeper waters that were previously inaccessible. Enhanced geothermal systems (EGS) are also gaining popularity, utilizing advanced drilling techniques to access heat from dry rock formations. Moreover, small modular nuclear reactors (SMRs) are progressing toward commercialization, providing a more adaptable and potentially safer alternative to conventional nuclear plants. Additionally, green hydrogen produced by electrolysis is emerging as a zero-emission solution for grid balancing and industrial use.

Regarding the decision-making process, selecting the appropriate weights is essential to achieve the most suitable assessment based on stakeholders' interests. In this work, we used a simple approach illustrating different scenarios and their impacts. Still, we recommend that future work include an additional step involving Multi-Criteria Decision Analysis (MCDA) methods. For example, the ELECTRE III, AHP, TOPSIS, SWARA/ARAS methods, or combinations of these.

SUPPLEMENTARY

The raw data and calculations for each graph presented in this paper have been provided in an accompanying Excel file.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Conceptualization: J.D.G-R, M.N., S.C.; Methodology: J.D.G-R, M.N., S.C.; Analysis: J.D.G-R, M.N., S.C.; Data curation: J.D.G-R; Writing: J.D.G-R; Review and editing: J.D.G-R, M.N., S.C. All authors had read and approved the final version of the manuscript.

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