Economic and Social Considerations for the Future of Nuclear Energy in Society

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Contents

List of abbreviations and acronyms

ADP Abiotic Depletion Potential

CFC Chlorofluorocarbons

CHP Combined Heat and Power

CO2e Equivalent in carbon dioxide

Ec-LCA Economic Life Cycle Assessment

EU European Union

En-LCA Life Cycle Assessment

EROI Energy Return on Investment

GDP Gross Domestic Product

GHG Green House Gases

HLO High Level Objective

IAEA International Atomic Energy Agency

iRES Intermittent renewables (wind, solar)

ISF Inherent Safety Feature

LCOE Levelized Cost of Electricity

NMVOC Non-Methane Volatile Organic Compounds

NOx Nitrogen Oxides

ODP Ozone Depletion Potential

O&M Operation and Maintenance

PDF Potentially Disappeared Fraction

POPCP Photochemical Oxidant Creation Potential

PM2.5 Particulate Matter Smaller Than 2.5 Micrometers

RDI Research, development, and innovation

REEs Rare Earth Elements

SDG Sustainable Development Goals

SMR Small modular reactor

So-LCA Social Life Cycle Assessment

SOx Sulphureous Oxides

S1 First set of weights

S2 Second set of weights

TRL Technologically Readiness Level

UN United Nations

VOC Volatile Organic Compounds

Executive Summary

The ECOSENS project undertakes a comprehensive assessment of the sustainability performance of nuclear power across its entire life cycle, taking into account the latest advancements in nuclear technologies. This assessment is important as nuclear power remains a valuable component of the global energy mix, particularly in the context of achieving long-term energy sustainability and meeting climate goals. Recognizing the dynamic nature of the energy transition, the assessment is conducted comparatively, encompassing not just nuclear power but also the other key energy technologies driving this transition—namely, intermittent renewables (wind and solar), hydropower, and natural gas.

These technologies are integral to the energy policies at the European Union (EU) level, where each plays a distinct role in the collective effort to reduce carbon emissions, enhance energy security, and promote sustainability. However, the emphasis and adoption of these technologies vary across EU member states, influenced by regional resources, policy priorities, and socio-economic factors. By including a comparative analysis, the ECOSENS project aims to provide a balanced and nuanced understanding of how each energy technology can contribute to the overarching goals of the energy transition, both within the EU framework and at the national level. Moreover, the ECOSENS project attempts to demonstrate components of public participation in sustainability assessment, in order to later formulate some recommendations on how this useful aspect can be requested by stakeholders and incorporated by governments.

The current report presents the results of a full-scale demonstration of the ECOSENS methodology for the lifecycle sustainability assessment of key energy technologies, including elements of stakeholder participation, with particular attention to the assessment obtained by nuclear power. The report is structured in five sections, each detailing a specific aspect of the assessment process.

The introductory section outlines the decision-making process for determining the energy mix, highlighting the potential contributions of stakeholder participation. This process involves a careful balancing of economic, environmental, and social considerations, such as resource availability, economic viability, environmental impact, technological feasibility, and political and social factors. The quality and sustainability of the decisions may be directly linked to the level of informed participation from stakeholders, including the general public. Informed participation requires that stakeholders have an adequate understanding of the complex technical, economic, and environmental aspects involved in energy systems. However, one of the main challenges is the widespread lack of access to clear, accurate information and the necessary education to grasp these complexities. The current assessment seeks to bridge this gap by providing resources to reduce misinformation or lack of information, and enhance the knowledge of stakeholder participants.

The second section details the methodology developed for the assessment, which was rigorously constructed by mapping and integrating elements from existing frameworks used to assess energy technologies, particularly nuclear power. The methodology includes a set of 62 indicators and sub-indicators, allowing assessment on aspects such as life cycle perspective, technological neutrality,

environmental impact assessment, and considerations of social and economic equity. The final score for each technology is derived by multiplying the average scores per indicator by their respective weight and summing for all indicators.

The third section describes the preparation and execution of the assessment process. It presents the composition of the participant groups, the information provided to them, and the set of questionnaires used. Practical details of the process, such as how participants were guided through the assessment and how their input was collected and analyzed, are also discussed.

The fourth section presents the results of the assessment, structured into several subsections. The first three subsections are dedicated to the results of lifecycle assessment performed for the three pillars of sustainability: Environment, Economics, and Social. Attention is brought to the dispersion of opinions underlying certain obtained average (mean) scores. The fourth subsection provides an aggregated result, or "figure of merit," for each energy technology within these pillars, followed by a general figure of merit that considers all the assessment indicators. In this subsection, results were aggregated using equal weightings across all indicators. The next subsection introduces a set of varying weightings to explore how different levels of importance assigned to specific indicators affect the final figure of merit. Finally, considerations on the role of nuclear power in the energy transition are discussed in terms of this energy's strongest and weakest performances as revealed by the sustainability assessment. The particular role of new nuclear technologies is laid out.

The fifth section details what is learned from the assessment about the potential role of nuclear power in the energy transition, with explicit consideration of both strengths and weaknesses of classical and new technologies.

The sixth section offers conclusions drawn from the assessment. It synthesizes the insights gained from the assessment, discussing the overall sustainability performance of the assessed energy technologies. The conclusions highlight the relative strengths and weaknesses of each technology in the context of the energy transition and provide recommendations for policy and decision-making based on the assessment findings.

1 Introduction: Sustainability in the energy sector and expected role of nuclear power

Sustainability in the energy sector is a critical objective for the European Union (EU), aimed to ensure secure, competitive, and environmentally sustainable energy generation, transport, and use. The EU's commitment to sustainability is driven by the need to mitigate climate change, reduce greenhouse gas emissions, and transition to a low-carbon economy. As a global leader in climate action, the EU has set ambitious targets for reducing carbon emissions, especially by increasing the share of renewable energy, and improving energy efficiency.

Sustainability in energy is a multifaceted goal that requires coordinated efforts at local, national, and international levels. The EU's proactive approach, guided by the principles of the European Green Deal [1], sets a path towards a cleaner, more sustainable, and prosperous future for all its citizens. By embracing renewable energy, enhancing efficiency, ensuring security, fostering innovation, and prioritizing climate action, the EU is paving the way for a sustainable energy transition that benefits both people and the planet.

At the level of a country or a region, the performances of the energy system are closely related to the energy mix and the performances of the included technologies. The energy mix refers to the combination of different energy sources a country uses to meet its energy demands. When a country selects its energy mix, the process involves careful consideration of various factors to balance economic, environmental, and social needs:

(1) Resource availability (countries first assess their available domestic energy resources, such as fossil fuels, renewable resources, nuclear, and other energies. A nation rich in natural gas, for instance, might rely more heavily on that resource. If domestic resources are limited, countries consider the feasibility of importing energy, which includes appraising the geopolitical and economic stability of supplier nations)

(2) Economic considerations (considering the different costs of generating energy from different sources; necessary investment and infrastructure, energy security)

(3) Environmental impact (considering the commitment to reducing greenhouse gas emissions under international agreements like the Paris Agreement; beyond global concerns, countries must consider local environmental impacts, such as air pollution from coal plants or ecosystem disruption from large hydroelectric projects)

(4) Technological development (as technology improves, previously costly or unreliable sources, like solar or wind, become more viable; investments in R&D can lead to breakthroughs that shift the energy mix over time)

(5) Political and social factors (governments play a crucial role in shaping the energy mix through subsidies, taxes, and regulations. Policies promoting renewable energy or imposing carbon taxes on fossil fuels can significantly influence the mix. Social acceptance is vital, particularly for projects with significant local impacts, like nuclear plants or large wind farms. Public opposition can delay or prevent the development of certain energy projects. Energy trade, international partnerships, and adherence to global agreements also shape a country's energy decisions)

(6) Market dynamics (global energy market influences domestic energy prices, availability, and competition; countries must navigate these dynamics to ensure a stable and affordable energy supply)

(7) Long-term planning (considering the long-term sustainability of the energy mix, ensuring that it can meet future energy needs without depleting resources or causing irreparable environmental damage; as the global energy landscape changes, countries must remain adaptable, adjusting their energy mix in response to new challenges, opportunities, or technological developments)

By balancing these factors, countries can craft an energy mix that meets their immediate needs while planning for future sustainability and resilience. The goal is to ensure a reliable, affordable, and clean energy supply that supports economic growth and environmental protection.

It should be noted that the estimation of the sustainability impacts requires taking into consideration the entire cycle of each energy generation, therefore considering the extraction of ores, manufacturing of the materials, component and systems, operation, decommissioning, waste management and recycling, site remediation and greening. Sometime, technology developers mask many of the impacts, by publishing data restricted to the operational phase.

The decision-making process for determining a country's energy mix is critical, with far-reaching implications for the economy, environment, and society. Given the complexity and long-term impact of these decisions, it is essential to involve a broad range of stakeholders, including the general public, in the process. Seeking inclusive participation should not only enhance the legitimacy of the decisions made but also help to align the energy mix with the principles of sustainability, which are crucial for the well-being of current and future generations:

(1) Legitimacy and democratic accountability - In a democratic society, decisions that affect the entire population should not be made solely by a small group of policymakers or industry experts. The energy mix will determine how a country meets its energy needs, affects economic development, and shapes environmental outcomes for decades. Including stakeholders such as local communities, environmental groups, industry representatives, and the general public in the decision-making process ensures that diverse perspectives are considered. This inclusion fosters greater transparency and accountability, as the decision-makers must justify their choices to a broader audience. When the public feels that their voices are heard and valued, it increases trust in the process and the willingness to support and adhere to the outcomes.

(2) Sustainability and long-term vision - Sustainability is a critical consideration in shaping a country's energy mix. An energy strategy that prioritizes sustainability seeks to balance environmental protection, economic viability, and social equity. Stakeholders, particularly environmental groups and local communities, often have a deep understanding of the long-term impacts of energy choices on the environment and society. Their participation can ensure that the energy mix incorporates renewable energy sources, reduces greenhouse gas emissions, and minimizes the environmental footprint of energy production. Additionally, involving the public can lead to a more holistic view of sustainability, one that considers not just environmental factors but also social justice issues, such as energy access and affordability.

(3) Enhancing social acceptance and reducing conflict - Energy projects, particularly those involving large infrastructure like wind farms, nuclear plants, or hydroelectric dams, can significantly impact local communities. Without early and meaningful consultation, these communities may resist or oppose such projects, leading to delays, increased costs, or even project cancellations. Engaging stakeholders from the outset helps to identify and address concerns, negotiate compromises, and ensure that the benefits of energy projects are equitably distributed. When

people feel they have a say in decisions that affect their lives, they are more likely to support those decisions, leading to smoother implementation and less social conflict.

(4) Aligning with global sustainability goals - Many countries have committed to global sustainability goals, such as the United Nations Sustainable Development Goals (SDGs) and the Paris Agreement on climate change. These commitments require integrating sustainability into all aspects of national policy, including energy planning. Stakeholder participation is essential in aligning the national energy mix with these global goals. Civil society organizations, in particular, play a crucial role in holding governments accountable to their international commitments and ensuring that national policies do not deviate from the path of sustainability. By involving these stakeholders, countries can ensure that their energy strategies contribute to global efforts to combat climate change and promote sustainable development.

(5) Encouraging innovation and diverse solutions - Stakeholder participation can stimulate innovation by bringing together a wide range of ideas and expertise. The energy sector is rapidly evolving, with new technologies and approaches emerging regularly. By involving stakeholders from various sectors, including academia, industry, and civil society, the decision-making process can benefit from a diverse set of solutions. Public consultations, for example, can obtain input from community-driven renewable energy projects, while industry input can provide insights into the latest technological advancements. This collaborative approach can lead to a more resilient and adaptive energy mix that is better equipped to meet future challenges.

The selection of a country's energy mix is a decision of immense importance, with long-lasting implications for the economy, environment, and society. To ensure that these decisions are sustainable, equitable, and widely accepted, it is crucial to involve a broad range of stakeholders, including the general public, in the decision-making process. By fostering transparency, enhancing social acceptance, encouraging innovation, and aligning with global sustainability goals, stakeholder participation helps to ensure that the energy mix not only meets current needs but also safeguards the well-being of future generations. We cannot assert a direct causal link between participation and sustainability, especially considering the varying degrees of participation and the numerous subsequent actions and decisions required to implement stakeholder input, but the participation may contribute to more sustainable decisions.

When shaping the energy mix, decision quality and sustainability can be directly influenced by the level of informed participation by stakeholders, including the general public. **Informed participation means that stakeholders not only have a voice in the decision-making process but also possess a level of knowledge and understanding necessary to engage meaningfully with complex energy issues**. This informed participation is crucial for several reasons, particularly in enhancing the sustainability of energy policies and practices.

Energy mix decisions are inherently complex, involving technical, economic, environmental, and social considerations. For participation to be meaningful, stakeholders must be equipped with the relevant knowledge and information to engage with these issues critically. Informed stakeholders can contribute valuable insights, question assumptions, and propose innovative solutions that might otherwise be overlooked. For instance, understanding the environmental impact of different energy sources may enable stakeholders to advocate for more sustainable options, such as renewables, over more harmful fossil fuels. This informed input can lead to more robust and effective decision-making, helping to ensure that the chosen energy mix is not only practical but also aligns with broader sustainability goals.

The energy sector is often subject to missing information, misinformation, and misconceptions, which can distort public perceptions and influence policy decisions in ways that are not conducive to sustainability. Informed participation helps to counteract these challenges by providing to stakeholders a measure of accurate, evidence-based information. To the extent that this information is integrated by the participants, this may reduce the risk of stakeholder input being swayed by myths or unfounded fears, such as exaggerated dangers of nuclear energy or the perceived inefficiency of renewable sources. By fostering well-informed public discourse, the decision-making process can focus on the real issues and challenges, leading to more sustainable outcomes.

Sustainability requires a long-term commitment, not only from governments and businesses but also from the general public. Informed participation has the potential to raise awareness about the long-term benefits of sustainable energy practices, such as reduced greenhouse gas emissions, improved public health, and enhanced energy security. However, while individuals may express greater commitment in theory, this does not always translate into consistent behavior in practice. When stakeholders understand these benefits and which trade-offs may be envisioned, they may be more likely to support policies and initiatives that may involve short-term sacrifices but yield significant long-term gains. Such public support is crucial in democracies for the successful implementation of energy policies that prioritize sustainability.

Sustainability is a central goal in contemporary energy planning, aiming to balance current energy needs with the preservation of resources and environmental quality for future generations. Informed participation plays a key role in achieving this balance. When stakeholders, including the general public, are educated about the implications of different energy sources—such as their carbon footprints, resource requirements, and long-term environmental impacts—they may be more likely to reflect on sustainable energy policies. Public awareness campaigns, educational programs, and transparent communication by governments and energy companies may support individuals to make informed choices, whether by approving of sustainable energy policies or adopting energy-saving practices in their daily lives. Such collective action remains an essential goal to help drive the transition to a more sustainable energy system.

The transition to a sustainable energy mix must be equitable, ensuring that all segments of society benefit from the changes and that vulnerable groups are not disproportionately affected. Informed participation helps to highlight the social dimensions of energy decisions, such as the impact of energy prices on low-income households or the need for job creation in renewable energy sectors. When stakeholders are informed, they might better advocate for policies that address these equity concerns, pushing governments to ensure that the energy transition is not only sustainable but also fair and inclusive.

Informed participation appears vital for ensuring that decisions related to a country's energy mix are both effective and sustainable. Ideally, by equipping stakeholders with the knowledge and understanding needed to engage with complex energy issues, informed participation can enhance the quality of decision-making, promote accountability, counter misinformation, and foster long-term commitment to sustainable practices. Furthermore, adequate informed participation favors transition to a sustainable energy system both inclusive and equitable, benefiting all members of society. As countries around the world grapple with the challenges of climate change and resource depletion, the role of informed participation in shaping sustainable energy policies cannot be overstated.

One of the main difficulties in ensuring informed stakeholders in energy mix decisions is the complexity of energy systems, which require a deep understanding of technical, economic, and environmental factors. Many people lack access to clear, accurate information or the necessary education or training to grasp these complex issues, making meaningful participation challenging. Additionally, misinformation and conflicting interests can skew public perceptions, leading to confusion and polarized opinions. The fast pace of technological advancements in the energy sector further complicates the situation, as stakeholders may struggle to keep up with the latest developments.

Building on these considerations, it is evident that in many cases, the general public and some stakeholders may lack an informed understanding of the true impacts of various energy technologies. The current assessment aims to address this gap by providing some resources to reduce the effects of misinformation and missing knowledge. In the ECOSENS assessment exercise, participants who helped to assess energy technologies crucial to the energy transition process—such as intermittent renewables, hydro, nuclear, and gas—were encouraged to engage with representative materials and critically reflect on different perspectives. Before assigning an assessment mark for each indicator under assessment, participants were invited to consult synthesis “fiches” summarizing the latest key findings from the literature regarding the comparative sustainability performance of different energy production modes. The relevant references were indicated. Participants are also encouraged to consult any additional resources to further clarify their understanding and ensure a well-informed contribution to the decision-making process.

On the fiches developed for this assessment, each indicator was described in terms of both specific metrics and the varying performance estimates, observations or interpretations found in the literature. When data were available, the fiches included a range of values, typically presenting the spectrum from minimum to maximum sustainability performance as reported by different sources. This comprehensive presentation allows participants, especially those with limited prior knowledge of the indicators, to better understand the nuances involved. By exploring the full range of data and interpretations, participants could move beyond initial assumptions and progress toward a more informed and nuanced decision. This approach empowers stakeholders to make judgments grounded in a broader understanding of the complexities associated with each indicator.

In such an exercise, participants who feel they already possess sufficient knowledge or hold strong opinions may choose to bypass the associated materials and proceed directly to answering the assessment questions (assigning a sustainability mark to each indicator). This bypass, however, increases the risk of biases influencing their responses, as these participants might rely on preconceived notions rather than considering the full scope of information. To mitigate the impact of such biases, one effective strategy is to broaden the pool of participants involved in the assessment. By including a diverse and larger group of stakeholders, the range of perspectives can help balance individual biases, leading to more comprehensive and representative outcomes. Additionally, encouraging even knowledgeable participants to review the provided materials can promote reflection and a more balanced assessment, further enhancing the credibility of the assessment process.

2 Methodology for the entire life cycle assessment

The methodology was meticulously developed by mapping existing frameworks [2] for the assessment of energy technologies, with particular emphasis on nuclear power, and carefully selecting the most valuable and relevant procedural elements and indicators to suit the current objectives. The selection process was guided by a set of core principles to ensure a comprehensive and balanced assessment:

1. Adopt a life cycle perspective: Every stage of a technology's life cycle, from resource extraction to disposal, is considered in the assessment.

2. Maintain technological neutrality: Each energy technology is assessed on its merits through a large set of indicators, without favouring a priori any particular technology.

3. Assess environmental impacts: Thorough consideration of environmental impacts is enabled, using indicators including carbon footprint, air and water pollution, land use, resource depletion, and biodiversity effects.

4. Approach social and economic equity: The distribution of benefits and burdens across different social and economic groups is assessed through several indicators, ensuring that equity is a central consideration.

5. Consider health and safety risks: Indicators of both worker safety and public health risks are assessed to understand the potential hazards associated with each technology.

6. Assess resource efficiency and circular economy potential: Indicators of resource use efficiency are assessed, alongside the potential for technologies to contribute to a circular economy.

7. Consider resilience and adaptation: Indicators of the ability of technologies to withstand and adapt to climate change and other external stressors are also provided for assessment.

A detailed explanation of the methodology's development process is provided in [2]. To structure the assessment, three pillars commonly referenced in the appraisal of sustainability were selected:

1. Environmental Life Cycle Assessment (En-LCA): Assesses the environmental impacts throughout the technology's life cycle.

2. Economic Life Cycle Assessment (Ec-LCA): Assesses the economic performance and cost-effectiveness over the technology's life cycle.

3. Social Life Cycle Assessment (So-LCA): Assesses the social impacts, including issues related to equity, health, and safety, across the life cycle.

Correspondingly, three High-Level Objectives (HLOs) were formulated to guide the assessment:

1. Contribution to Planetary Wellbeing: Focuses on the environmental sustainability and long-term viability of the energy technologies.

2. Reliability and Resilience of Supply: Ensures that the energy supply is stable, secure, and adaptable to future challenges.

3. Social Feasibility: Assesses the social acceptability and fairness of the energy technologies, considering both current and future generations.

This structured approach is intended to provide a robust and holistic framework for assessing the sustainability and overall performance of various energy technologies.

The development of the methodology was significantly enriched by incorporating insights and feedback from experts and stakeholders, gathered during a dedicated workshop in Brussels [3]. This collaborative approach ensured that the methodology was not only theoretically sound but also practically relevant and aligned with the diverse perspectives of those directly involved in the energy sector or otherwise involved in sustainability studies or advocacy.

For the three defined assessment areas—Environmental Life Cycle Assessment (En-LCA), Economic Life Cycle Assessment (Ec-LCA), and Social Life Cycle Assessment (So-LCA)—a comprehensive set of 32 carefully selected indicators was established. These indicators were distributed across the three areas as follows:

(1) Environmental Life Cycle Assessment (En-LCA): 10 indicators were chosen to assess the environmental impacts of energy technologies, including metrics such as greenhouse gas emissions, air and water pollution, land use, resource depletion, and impacts on biodiversity.

(2) Economic Life Cycle Assessment (Ec-LCA): 9 indicators were selected to assess the economic performance of the technologies. These indicators cover aspects like cost-effectiveness, energy return on investment (EROI), market competitiveness, and potential for economic development.

(3) Social Life Cycle Assessment (So-LCA): 13 indicators were identified to measure the social impacts of energy technologies. This includes factors like job creation, health and safety risks for workers and the general population, social equity, public acceptance, and contributions to social well-being.

These indicators, summarized in Table 2.1, provide a detailed and multi-faceted framework for assessing the sustainability and overall performance of energy technologies. By capturing a broad range of environmental, economic, and social factors, this indicator set allows for a holistic assessment that aligns with the broader goals of sustainable development. The input from the Brussels workshop was instrumental in refining these indicators, ensuring they are both comprehensive and reflective of the current and future challenges in energy planning.

To ensure a thorough and nuanced assessment, some of the key indicators were further refined into sub-indicators, which provide additional layers of detail necessary for a comprehensive and fair assessment. These sub-indicators are designed to guide assessors in considering all relevant aspects of each indicator, ensuring that no critical elements are overlooked in the analysis.

In total, 42 sub-indicators have been defined across the various assessment areas. These sub-indicators help break down complex concepts into more manageable components, enabling a deeper exploration of specific factors that contribute to the overall performance of an energy technology. For example, within the Environmental Life Cycle Assessment (En-LCA), a primary indicator like "resource depletion" might be subdivided into sub-indicators that assess the depletion of specific resources such as water, minerals, and fossil fuels. Similarly, in the Economic Life Cycle Assessment (Ec-LCA), a general indicator like "cost-effectiveness" could be divided into sub-indicators that consider initial capital costs, long-term operational costs, and externalities.

Table 2.1 Indicators employed by the ECOSENS life cycle assessment

En-LCA	Ec-LCA	Soc-LCA
1.1 Carbon emissions 1.2 Land occupation and power density 1.3 Energy returned on investment 1.4 Impact on resources *(with 5 sub-indicators)* 1.5 Potential material recyclability 1.6 Emissions, other than Carbon *(with 4 sub-indicators)* 1.7 Impact on life and ecosystems under normal operation *(with 7 sub-indicators)* 1.8 Impact of generated wastes *(with 4 sub-indicators)* 1.9 Impact of accidental situations *(with 2 sub-indicators)* 1.10 Mitigation of accidents *(with 3 sub-indicators)*	2.1 Capacity factor 2.2 Global efficiency 2.3 Cost *(with 3 sub-indicators)* 2.4 Cost for system integration *(with 5 sub-indicators)* 2.5 External costs 2.6 LCOE Levelized Cost of Electricity 2.7 Macro-economic impact 2.8 Applicability for cogeneration 2.9 Level of standards generated, rules and control *(with 3 sub-indicators)*	3.1 Jobs created *(with 3 sub-indicators)* 3.2 Impact on the local/regional business (partner with other business) 3.3 Additional goods and services created 3.4 Value of the knowledge generated and maintained for the future 3.5 Impact on education 3.6 Contribute to the reduction of inherited burdens (toxic wastes, military stocks) 3.7 Impact on health improvement 3.8 Impact on poverty 3.9 Societal-level adoption of the technology 3.10 Existing investment in RDI to develop the technology 3.11 Dependency on government support 3.12 Risks *(with 2 sub-indicators)* 3.13 Equality of opportunities *(with 2 sub-indicators)*

This structured approach with sub-indicators allows for a more granular analysis, helping assessors to capture subtle variations and complexities that might be missed with broader indicators alone. It also supports consistency in assessment by providing clear criteria that must be met, reducing the potential for subjective bias and enhancing the reliability of the assessment process. By incorporating these sub-indicators, the methodology not only improves the precision of the assessments but also aligns more closely with the principles of transparency, completeness, and equity in assessing the sustainability of energy technologies.

The complete list of indicators and sub-indicators is presented in Table 2.2.

Table 2.2 Complete list of indicators and sub-indicators of ECOSENS methodology

Environmental Life Cycle Assessment (En-LCA)	
1.1	Carbon emissions
1.2	Land occupation
1.3	Energy returned on investment
1.4.1	Operational water consumption

1.4.2	Abiotic resources depletion
1.4.3	Depletion of fossil fuels
1.4.4	Excessive use of resources useful for the life sustaining
1.4.5	Exhausting of rare resources
1.5	Potential material recyclability
1.6.1	Emissions (other than C) - NOx and SO2 emissions
1.6.2	Emissions (other than C) - Ozone depletion potential
1.6.3	Emissions (other than C) - Photochemical oxidant creation potential
1.6.4	Emissions (other than C) - Cumulative lifecycle emissions of NMVOC and PM2.5
1.7.1	Impact on life and ecosystems (under normal operation)- Human toxicity potential
1.7.2	Impact on life and ecosystems (under normal operation)- Human health/mortality impact
1.7.3	Impact on life and ecosystems (under normal operation)- Ecotoxicity
1.7.4	Impact on life and ecosystems (under normal operation)- Acidification and eutrophication potential
1.7.5	Impact on life and ecosystems (under normal operation)- Freshwater ecotoxicity
1.7.6	Impact on life and ecosystems (under normal operation)- Marine ecotoxicity
1.7.7	Impact on life and ecosystems (under normal operation)- Biodiversity of the used land
1.8.1	Impact of generated wastes - Chemical (generated) waste volumes
1.8.2	Impact of generated wastes - Radioactive wastes (generated)
1.8.3	Impact of generated wastes - Maturity of the approach (experience and effectivity in waste management)
1.8.4	Impact of generated wastes - Long-term effect of deposited wastes
1.9.1	Impact of accidental situations - Impact of the accidents (anticipated, design base)
1.9.2	Impact of accidental situations - Impact of severe accidents (considering mitigation/prevention…)
1.10.1	Mitigation of accidents - Inherent safety
1.10.2	Mitigation of accidents - Passive systems
1.10.3	Mitigation of accidents - Safety by design
Economic Life Cycle Assessment (Ec-LCA)	
2.1	Capacity factor
2.2	Global efficiency

2.3.1	Cost - Cost of the investment (capital cost)
2.3.2	Cost - Cost of operation (including fueling and maintenance)
2.3.3	Cost - Cost of decommissioning (including environmental remediation)
2.4.1	Cost for system integration – Maneuverability
2.4.2	Cost for system integration – Load following
2.4.3	Cost for system integration – Stability
2.4.4	Cost for system integration – Easy to be integrated in local/regional grids
2.4.5	Cost for system integration – Realistic solution for large scale storage
2.5	External costs
2.6	LCOE Levelized Cost of Electricity
2.7	Macro-economic impact
2.8	Applicability for cogeneration
2.9.1	Level of standards generated, rules and control - Maturity of the authorization process
2.9.2	Level of standards generated, rules and control - Level of industrial codes and standards
2.9.3	Level of standards generated, rules and control - Needs for technical support
Social Life Cycle Assessment (So-LCA)	
3.1.1	Jobs created - Direct high-education jobs
3.1.2	Jobs created - Jobs in contributing industries
3.2	Impact on the local/regional business (partner with other business)
3.3	Additional goods and services created
3.4	Value of the knowledge generated and maintained for the future
3.5	Impact on education
3.6	Contribute to the reduction of inherited burdens (toxic wastes, military stocks)
3.7	Impact on health improvement
3.8	Impact on poverty
3.9	Social level adoption of the technology
3.10	Existing investment in RDI to develop the technology
3.11	Dependency on government support (funding/ incentives, such as tax credits or subsidies)
3.12.1	Risks - Level of risk reflected in insurance needs
3.12.2	Risks - Proliferation of sensitive materials

3.13.1	Equality of opportunities - Women's empowerment
3.13.2	Equality of opportunities - For minorities, vulnerable social groups, Indigenous peoples, children, people with disabilities

In preparing the assessment of energy technologies, weighting the scores for different indicators is a crucial step that reflects the varying importance of these indicators in the context of sustainability and decision-makers' strategic vision. Weighting by the exercise's planned beneficiaries (decision-makers) helps to ensure that the assessment process is most informative with regard to both the specific sustainability goals of a project and the broader objectives of the decision-makers.

Not all indicators carry the same weight when it comes to assessing sustainability performance. For instance, the carbon footprint of an energy technology might be deemed more critical than its impact on local employment, given the global priority to reduce greenhouse gas emissions. By assigning weights to different indicators, the assessment can prioritize those aspects that are most significant to the sustainability objectives. This allows the assessment to more accurately reflect the relative importance of various factors, ensuring that critical issues are given appropriate consideration in the decision-making process.

Sustainability assessments often involve trade-offs between different factors, such as balancing environmental impacts with economic benefits. Weighting allows decision-makers to express their preferences and priorities by emphasizing certain indicators over others. For instance, if reducing environmental impact is a top priority, indicators related to pollution and resource use might be weighted more heavily than economic or social indicators. This approach helps to navigate complex trade-offs and make more informed, nuanced decisions that reflect the true priorities of the stakeholders involved.

Weighting the scores for different indicators in sustainability assessments is essential for accurately reflecting their relative importance, aligning with strategic visions, enhancing decision-making accuracy, addressing trade-offs, and improving transparency. By assigning appropriate weights, decision-makers can ensure that their assessments are not only comprehensive but also tailored to their specific sustainability goals and priorities. This approach allows for a more nuanced and effective assessment of energy technologies, ultimately supporting more informed and balanced decision-making.

The methodology involves a threefold weighting:

(1) at the level of the indicator (considering the set of existing sub-indicators),

(2) at the level of pillar (High Level Objective),

(3) at the level of an energy technology.

Considering *N_Sj*=number of sub-indicators for the indicator indexed by *j*, *N_Ik*=the number of indicators for the HLO indexed by *k*, and *N_H*=number of HLOs we obtain:

$$S_{global} = \sum_{k=1}^{N\_H} (w\_H_k \sum_{j=1}^{N\_Ik} (w\_in_j \sum_{i=1}^{N\_Sj} (w\_si_i * S\_Si_i)))$$

where S_Si_i is the score assigned by the assessors to the sub-indicator *i* (of the indicator *j*), w_si_j is the weight for the sub-indicator *i*, w_in_j is the weight for the indicator *j* (of the HLO indexed by *k*), and S_{global} is the final score (the figure of merit for an assessed energy technology.

Each set of weights (at the level of indicators, HLO, and energy technology) is normalized to 1.

$$\sum_{k=1}^{N\_H} w\_H_k = 1, \quad \sum_{j=1}^{N\_Ik} w\_in_j = 1, \quad \sum_{i=1}^{N\_Sj} w\_si_j = 1$$

3 The assessment process

The assessment process represents the third important step in the methodology outlined in Fig. 3.1. This process is systematically structured into several stages. First, the appropriate type of assessment is selected (environmental, economic, social), depending on the specific objectives and context of the analysis. This step selects the indicators that will be assessed in the subsequent stages. Second, each indicator and sub-indicator is assessed in turn by individuals working alone. This stage involves consulting fiches to clarify (if necessary) understanding of the (sub-)indicator and to take note of performance or impact data as available. Third, the assessment data collected from the set of individual raters is processed quantitatively, and results and patterns of results are analyzed both quantitatively and qualitatively in order to interpret the findings. Finally, the process concludes with in-depth discussions and the reporting of findings. This stage targets clear communication of the results, highlighting key insights, trends, and recommendations for further reflection, assessment, or other action. Overall, this structured approach facilitates a rigorous and transparent assessment, which can contribute to well-informed decision-making.

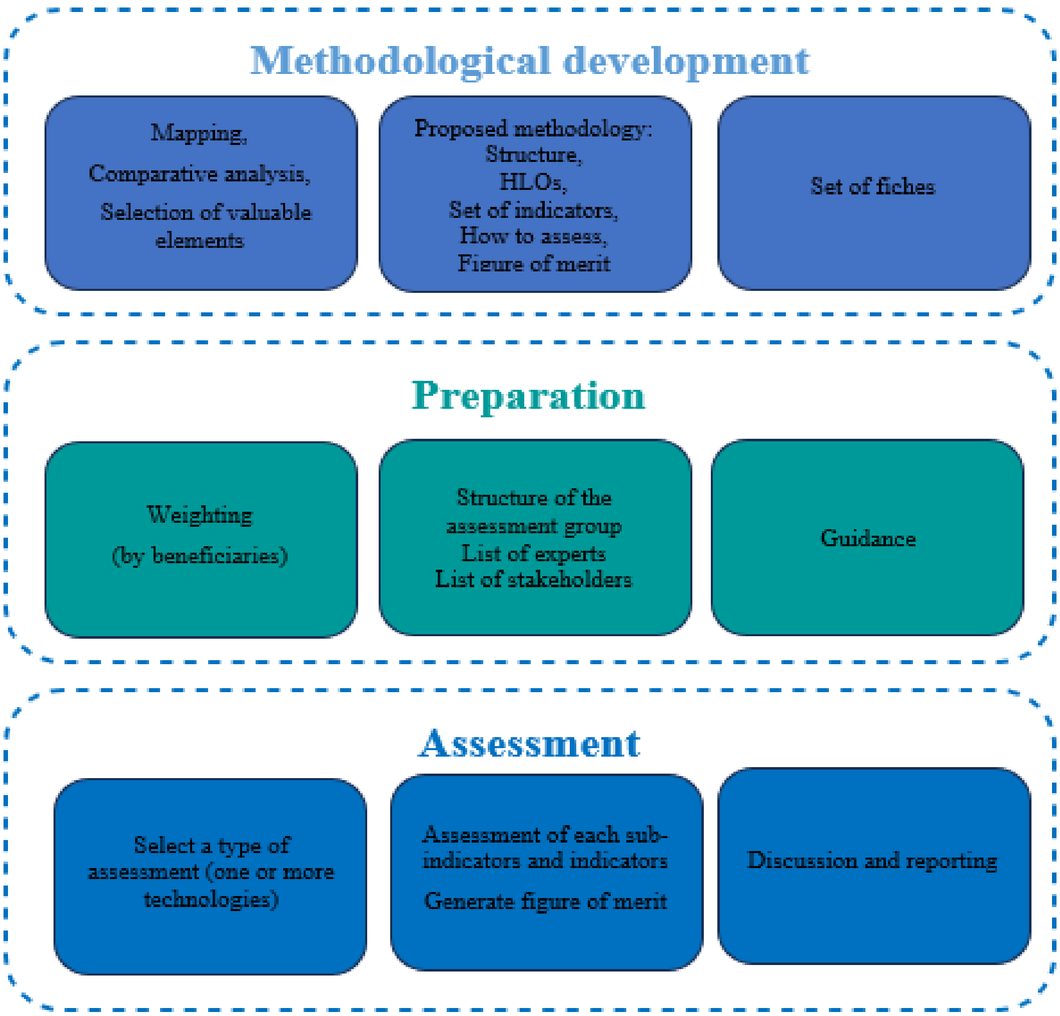


Fig.3.1 Steps of the ECOSENS life cycle assessment methodology

The current exercise is centered on assessing the potential role of nuclear power as a sustainable component of energy systems within the broader context of the energy transition. To gain a comprehensive perspective, this assessment is designed as a comparative analysis, examining nuclear power alongside the other major technologies driving the energy transition. These include: **intermittent renewable energy sources (iRES, such as wind and solar), hydropower,** and **natural gas**. By assessing these four key technologies, the analysis aims to highlight their respective strengths, weaknesses, and potential synergies in contributing to a more sustainable energy system. This comparative approach may offer valuable insights into the role each technology can play in the transition to cleaner energy, as well as the trade-offs involved in balancing reliability, scalability, and environmental impact.

For the sake of simplicity and efficiency, a structured set of questionnaires was developed to facilitate the data collection process. To streamline communication between the respondents and the research team, the Google Docs platform was employed, allowing easy distribution and completion of the questionnaires. The full set of 62 indicators and sub-indicators, presented above in Table 2.2, was broken down into seven distinct questionnaires, each focusing on a specific subset of the indicators, as follows:

- **Questionnaire 1 (Q1):** Environmental indicators and sub-indicators from 1.1 to 1.5
- **Questionnaire 2 (Q2):** idem, from 1.6.1 to 1.7.7
- **Questionnaire 3 (Q3):** idem, from 1.8.1 to 1.10.3
- **Questionnaire 4 (Q4):** Economic indicators and sub-indicators, from 2.1 to 2.4.5
- **Questionnaire 5 (Q5):** idem, from 2.5 to 2.9.3
- **Questionnaire 6 (Q6):** Social indicators and sub-indicators, from 3.1.1 to 3.7
- **Questionnaire 7 (Q7):** idem, from 3.8 to 3.13.2

This division of the questionnaires was designed to provide respondents with a manageable workload, aiming to limit the time required for completion to approximately one hour per questionnaire. By sequencing through multiple questionnaires at their own rhythm, the respondents were able to focus on smaller, more digestible segments of the overall assessment, which, in turn, was expected to improve the accuracy and quality of the responses. Additionally, this approach offered the flexibility to complete the questionnaires in stages, helping to maintain engagement throughout the data collection process.

To illustrate the structure and approach, the introductory section of Questionnaire 1 (Q1), the assessment scale utilized, and the format of a typical question are presented in Figures 3.2, 3.3, and 3.4 respectively. This structure aimed at clarity and ease of understanding for the respondents, and to facilitate efficient navigation through the questions without unnecessary confusion or complexity. This systematic approach was expected to facilitate more reliable data collection and enhance the overall quality of the assessment.

Respondents could easily access the background information and data relevant to each question by simply clicking on the title, which linked directly to the corresponding fiche. This streamlined system, ensuring that all relevant resources are readily available with just a single click, contributed to a more seamless data collection process. All fiches were uploaded to a dedicated webpage specifically designed as a centralized repository for the assessment. The simplicity of access minimized technical barriers, allowing respondents to focus on the content of the assessment rather than on how to find supporting materials. We consider that this is a particularly strong point of the assessment design, which enhanced respondents' overall experience by offering an intuitive and efficient way to handle multiple fiches without confusion or delay.

The fiches are available for consultation here: https://marianconst.wixsite.com/evaluare-sustenabili

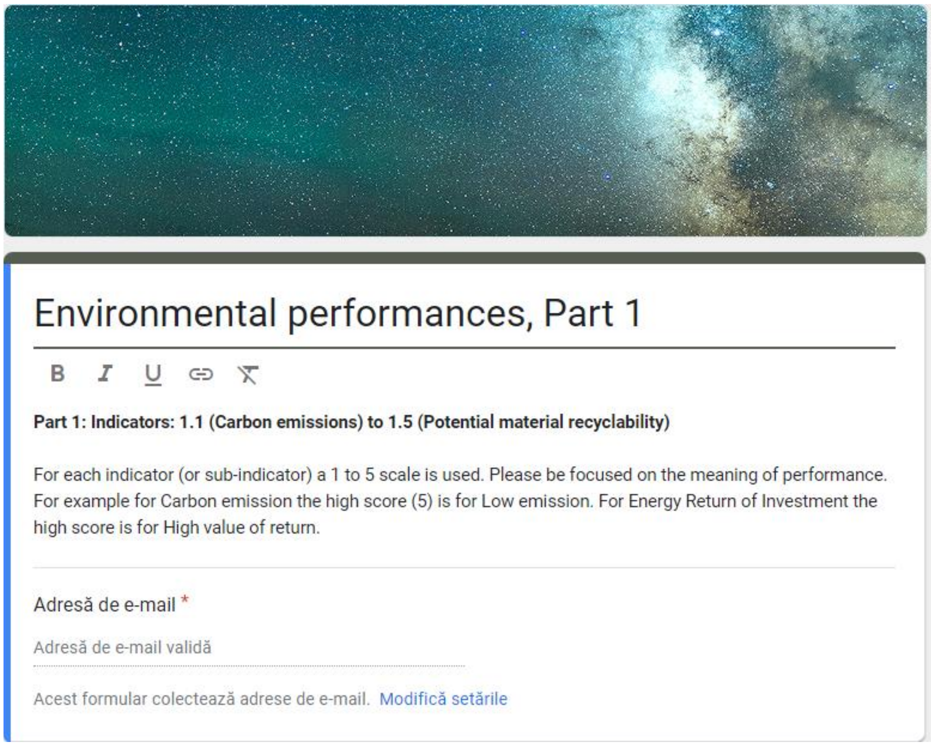


Fig.3.2 The introductory part of Questionnaire Q1

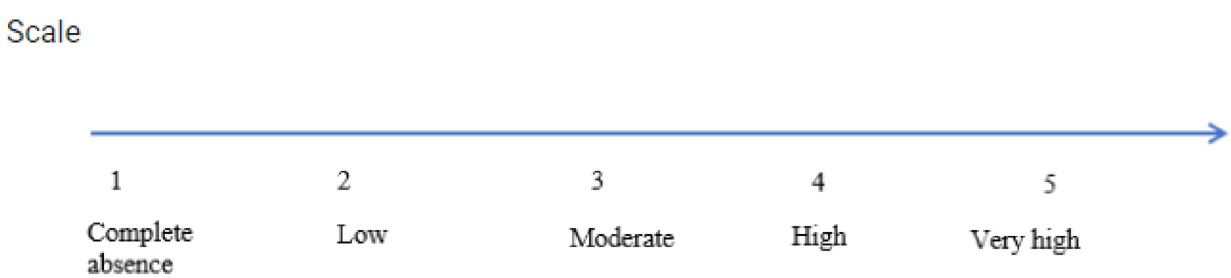


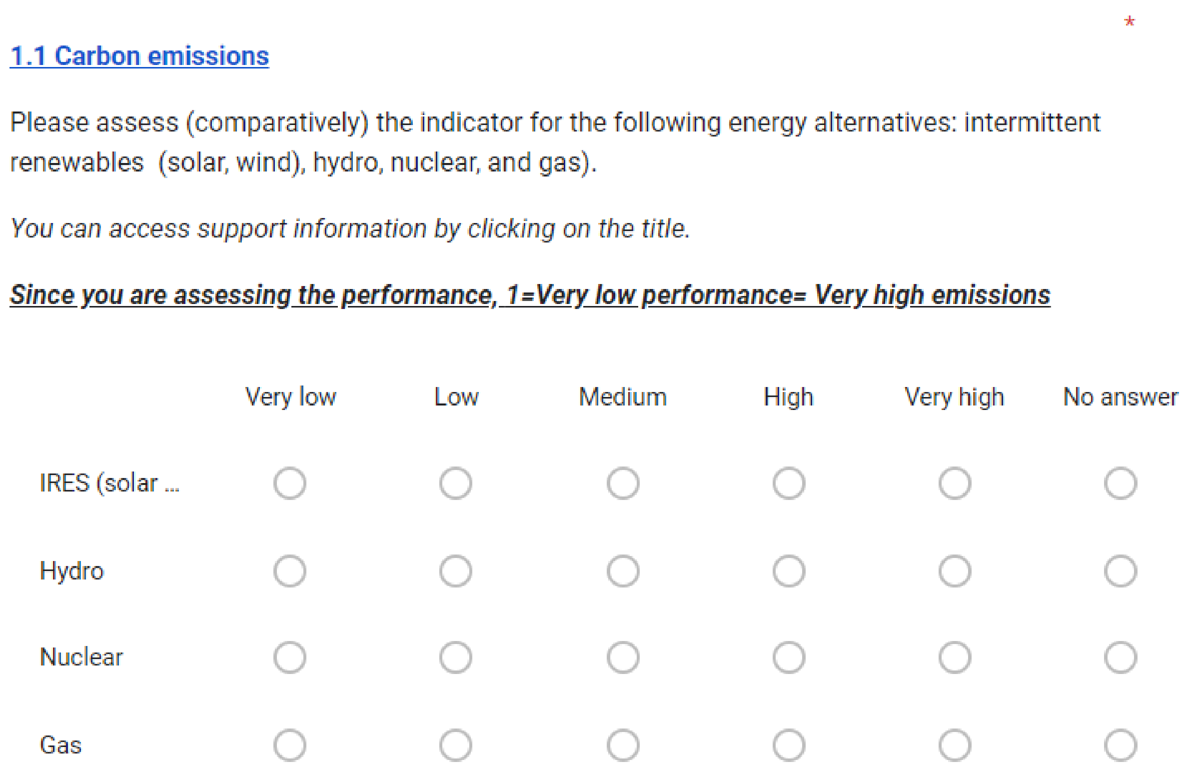
Fig.3.3 Scale used for the assessment

The recruitment of participants for this assessment was one of the most challenging tasks in the project. It was essential to ensure a balanced and diverse group of individuals with the appropriate expertise to provide meaningful insights. After careful consideration and facing multiple difficulties in engaging stakeholders in such effort, the following structure of participants was established:

> Group 1: Comprised of 20 representatives from partner organizations involved in the ECOSENS project. These participants were selected primarily for their expertise in socio-humanistic fields, which brought a valuable perspective to the assessment process, particularly in terms of understanding the social, ethical, and policy-related aspects of energy systems. While their technical

knowledge of energy systems may have been limited, their input was crucial for addressing the broader societal implications of the energy transition.

Group 2: Comprised of 20 participants with a strong technical background, though not necessarily specific to the energy sector. This group was responsible for providing more technical assessments, drawing on their expertise in engineering, science, or other relevant fields. The recruitment of this second group was handled by RATEN (Romanian Authority for Nuclear Energy Technologies), which ensured that individuals with the appropriate technical background were included. Although some participants in this group did not specialize in energy per se, their technical proficiency allowed them to contribute valuable insights into the operational and technological aspects of the energy transition.


1.1 Carbon emissions *

Please assess (comparatively) the indicator for the following energy alternatives: intermittent renewables (solar, wind), hydro, nuclear, and gas).

You can access support information by clicking on the title.

Since you are assessing the performance, 1=Very low performance= Very high emissions

	Very low	Low	Medium	High	Very high	No answer
IRES (solar ...						
Hydro						
Nuclear						
Gas						

Fig.3.3 Questionnaire 1; Question 1.1 concerning the “Carbon emissions” indicator, on each of four energy technologies.

By combining the socio-humanistic perspectives of Group 1 with the technical knowledge of Group 2, the selection process aimed to create a well-rounded panel of experts. This interdisciplinary approach was critical for generating a comprehensive assessment that considered both the societal and technical dimensions of energy systems. While challenging, the effort to curate this balanced panel favoured a robust and assessment of the multifaceted issues at hand.

In April 2024 (Group 2), respectively in May 2024 (Group 1), the respondents were invited to participate in the assessment by completing a series of seven questionnaires. To facilitate thoughtful and comprehensive responses, each questionnaire was distributed at a two-day interval. This approach was designed to provide respondents with time to reflect on each set of questions and to avoid rushing through the tasks. By spacing out the distribution of the questionnaires, the process aimed to ensure that respondents could give each section the attention it deserved without feeling pressured.

Additionally, a generous deadline was established, with respondents having approximately 30 days from the receipt of the final questionnaire to complete their responses. This extended timeframe was intentionally chosen to accommodate the varying schedules and workloads of the participants, thereby enhancing the likelihood of obtaining well-considered and high-quality feedback. The extended deadline not only allowed respondents to manage their time effectively but also ensured that the assessment was completed thoroughly and accurately, reflecting a careful consideration of each questionnaire's content.

4 Results and discussion

This section provides an overview of the results obtained from the participative assessment process. Detailed findings are presented in the following sub-sections:

- **Sections 4.1 (Environment), 4.2 (Economics), and 4.3 (Social)**: These sections present, for each pillar of sustainability, each area-specific indicator and sub-indicator and the average of the assessment scores obtained on each energy technology. Each indicator's score reflects respondents' judgments regarding the appraised sustainability performance which they were invited to consult in the accompanying documentation. Discussion in each sub-section delivers the author's expert interpretation of the results, adding deep knowledge of both the technologies and the indicators, and anticipating on the full set of findings.
- **Section 4.4**: This section aggregates the results at a higher level, focusing on the three life cycle assessment pillars: Environmental, Economic, and Social. The aggregation is performed using an equal weighting approach. The general Figure of Merit is calculated from this aggregated data, offering an overall assessment of the energy technologies in question.
- **Section 4.5**: Here, a specific set of weights is applied to the indicators to reflect their relative importance in the context of sustainability and strategic priorities. These weights were suggested, although with some hesitation, by stakeholders [3]. The results are detailed separately for each pillar—Environmental, Economic, and Social—as well as at an overall level. This weighted analysis allows for a nuanced understanding of how different factors contribute to the overall assessment, reflecting the specific priorities and goals of the decision-making process (in this demonstrator case: considering the potential contributions of different energy sources to a transition mix).
- **Section 4.6**: This section discusses the role of nuclear power in a transition energy mix, based on the perceptions expressed in the current sustainability assessment. Some expected changes to be introduced by the new technologies are explained.

Each section aims to provide clarity and in-depth understanding of the assessment process, indicators and findings, so that the analyses can support informed decision-making.

The assessment generated a large dataset due to the 62 (sub-)indicators, four technologies, and 40 participants, resulting in a total of 9,920 scores. This ECOSENS dataset remains available upon request to the authors.

To illustrate the data complexity, the complete spectrum of replies for the first two indicators (Carbon Emissions and Land Occupation) is presented in the form of radar graphs (see Fig. 4.1.1a and 4.1.2a).

To simplify the presentation, we chose to average the scores obtained for each (sub-)indicator and technology. The graphs included in this report display the *arithmetic mean* rating (the average of all 40 individual judgments[1]) for each energy technology. This choice makes it easier to read, interpret, and compare the judged performance of the four technologies on the given (sub)indicator without excessive detail.

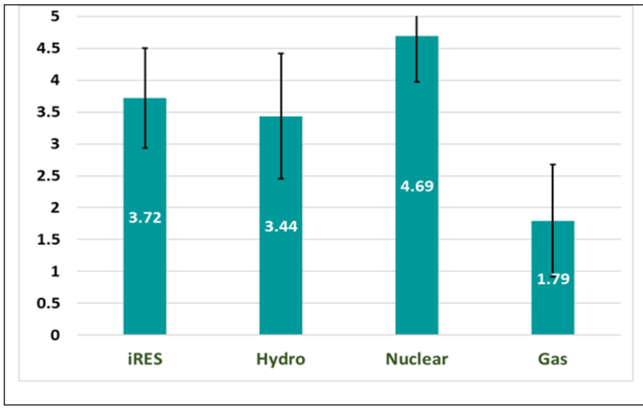
[1] The arithmetic mean, or average, is calculated by summing all the values observed, and dividing that sum by the number or count of values taken into the sum.

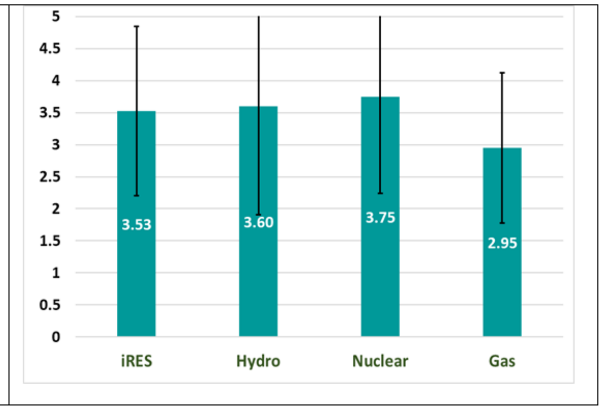
The report furthermore provides two types of supplementary information. For each (sub)indicator, a first graph displays on each mean rating the error bar (a thin black vertical line) representing *one standard deviation*, which is a manner of showing the degree of consensus within the dataset.

Box: What does the standard deviation error bar tell us?

The error bar representing the standard deviation (SD) indicates how spread out individual judgments are around the mean.[2] A shorter bar, or smaller standard deviation, signifies that most individual ratings were not very far from the overall mean, and tended to cluster around the mean value. By contrast, a longer bar, or larger standard deviation, signifies that individual judgments were more varied, distributed across a greater interval, and less tightly clustered around the mean.

As an illustration, these two figures drawn from the discussion respectively show smaller SDs (left, Fig. 4.1.1b) and larger ones (right, Fig 4.1.13).





On the left we see some shorter error bars: the SD for iRES covers approximately 1.5 points (from 3 to 4.5), meaning that most individual judgments fell within this interval around the mean score of 3.72. In the same figure, assessments of Nuclear are even more tightly grouped (a spread of 1 point around the mean of 4.69). These graphs convey an image of consensus on those technologies' performance.

By contrast, on the right we see that the individual judgments within each mean are more dispersed. An interval of more than 3 points is seen for the assessment of Hydro, while the interval for Nuclear is more than 2.5 points. This tells us that the persons performing the rating task were not in consensus.

In the latter case, caution will be exercised in interpretation of the mean score. It would not be appropriate to discuss such a mean score as if it represented a very strong agreement among raters. In our discussion below, we have arbitrarily chosen a standard deviation of more than 2.5 points to highlight such relative dissensus.

Related to the quality of the data set itself, it has to be noted that some individual responses may be considered marginal and may be eliminated based on the standard deviation method (if they lie too far outside the range of typical answers shown by the standard deviation). Due to the relatively low sample size (40 participants), removing marginal or extreme values could result in reducing of the size of data set, for some indicators in a critical manner. Moreover, each elimination should have a solid justification (beyond the standard deviation method) by examining the source and nature of the extreme values. For

[2] The SD is calculated such that more than two-thirds of individual responses can be found within the interval shown by the error bar; remaining responses (a little less than one third) may lie outside that range.

example, it could be observed that the direction of a single individual's ratings on a particular indicator is opposed to the direction selected by the majority of other raters (e.g., rating 1 or 2 when most others rated 4 or 5). It could be interpreted that the individual did not properly read the question and that if they had read it in the same way as all others, they might have reversed the sign and chosen corresponding positive (high) values rather than the comparatively negative (low) values; nonetheless, it is possible that the individual indeed intended to attribute low scores.

If such extreme values can by shown (by a clear and uniformly applied rule of interpretation) to be errors, eliminating them is justified. Otherwise removing them could introduce researcher bias (a judgment by the researchers as to what constitutes a "correct" answer or what the individual "meant" to say). In our study, with its relatively low sample size, it was difficult to differentiate between marginal values as errors and marginal values as relevant for the investigation. Therefore, the report presents the results without elimination of the marginal values. The present assessment exercise is considered to provide a test or demonstration of the functionality of the ECOSENS methodology. In future assessments the sample should be enlarged to allow removal of marginal values without the risk of reducing too greatly the sample size, which could result in diminishing the relevance of judgments on particular indicators.

Efforts to further characterize the data set and to elucidate these issues of interpretation and communication will be presented in Task 2.3, D2.5 (Recommendations for an improved methodology to assess sustainability).

4.1 Pillar 1, Environment

(I 1.1) - Carbon emissions

The sustainability indicator **"Carbon emissions"** for energy technologies refers to the amount of carbon dioxide (CO_2) and other greenhouse gases (GHGs), expressed as carbon dioxide equivalents (CO_2e), that are released into the atmosphere as a result of the production, distribution, and consumption of energy. This indicator is crucial for assessing the environmental impact of different energy technologies and is appraised by considering the entire life cycle of each technology, based on available data. Its metric is usually expressed in grams of CO_2 released for 1 kWh of electricity produced by a technology.

The lifecycle emissions consider all stages of an energy technology's lifecycle, including extraction of raw materials, manufacturing, transportation, installation, operation, and decommissioning. For example, while solar panels produce no emissions during operation, their lifecycle emissions include those from manufacturing and disposal.

The assessment on the sustainability performances for this indicator indicates, comparatively, judgments on how different energy sources contribute to the *reduction of Carbon emissions*. The possible scores range from 1 to 5, with higher scores indicating lower Carbon emission and therefore better sustainability. The results obtained by summing the score given to each energy source by each of the respondents and then averaging (dividing this sum by the number of respondents), thereby rendering *mean* scores, are presented in Fig. 4.1.1a, b & c.

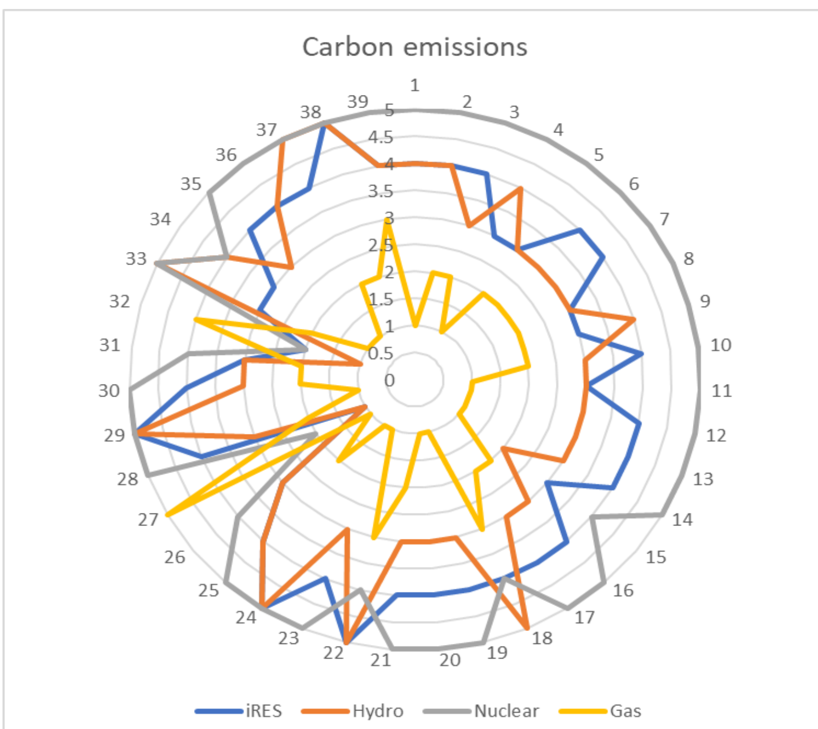


Fig. 4.1.1a, Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator I 1.1 – Carbon emissions, “radar” graph of data from the 40 respondents

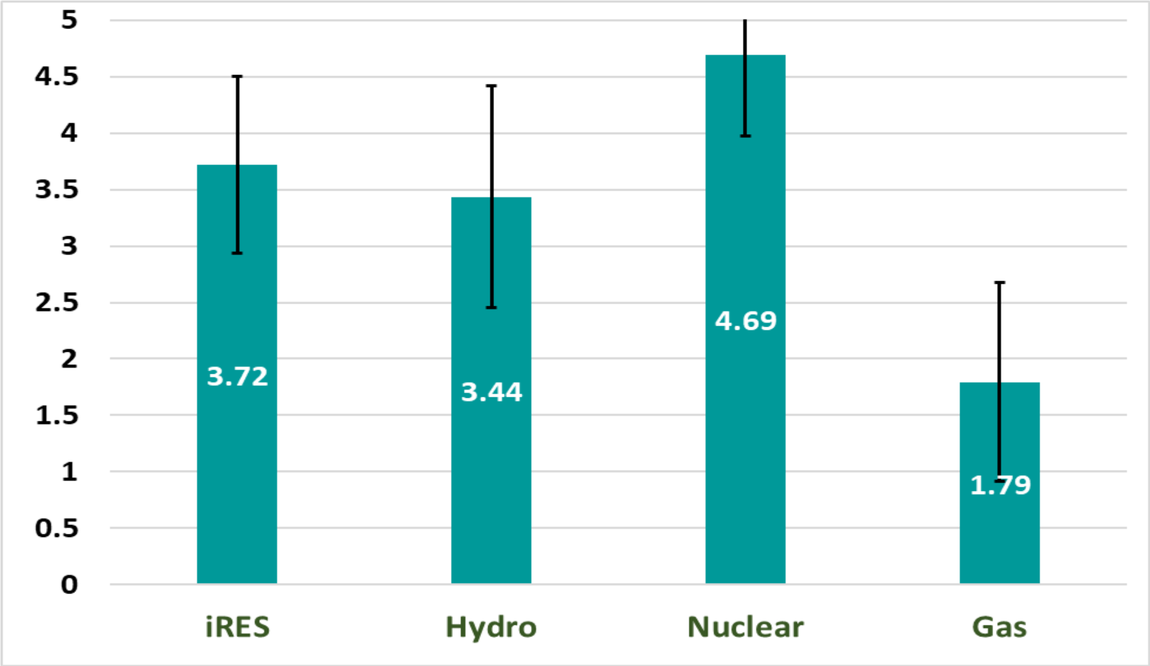


Fig. 4.1.1b, Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator I 1.1 – Carbon emissions

The mean scores[3] provide a clear hierarchy of carbon emissions performance among the energy sources considered. Nuclear energy (score: 4.69 out of a possible 5) leads in terms of minimizing carbon emissions, followed by intermittent renewables (3.72) and hydropower (3.44). Natural gas (1.79) lags significantly behind, highlighting the importance of transitioning away from fossil fuels to more sustainable energy sources in the fight against climate change.

- Nuclear energy (score: 4.69/5) receives the highest score, indicating that it is one of the most sustainable options in terms of carbon emissions. Nuclear power plants generate electricity through nuclear fission, which does not produce direct carbon dioxide (CO_2) emissions. This high score reflects the fact that nuclear energy is a low-carbon energy source, which is crucial for reducing GHGs emissions. The score suggests a strong alignment with sustainability goals focused on carbon reduction.

- Intermittent renewables (score: 3.72/5) includes energy sources like solar and wind, which have moderately high scores for carbon emissions. The score reflects the fact that while these sources are very low in carbon emissions during operation, they do have some associated carbon costs, primarily from the manufacturing, installation, and maintenance of equipment. Additionally, their intermittent nature may necessitate backup power from less sustainable sources, which could impact their overall carbon performance. However, as technology advances and energy storage solutions improve, the carbon footprint of intermittent renewables is expected to decrease further.

- Hydropower (score: 3.44/5) which generates electricity through the flow of water, has a moderate score. It produces very low carbon emissions during operation, like other renewables. The lower score relative to intermittent renewables may be due to the environmental impact associated with large-scale hydropower projects, such as habitat disruption, methane emissions from reservoirs, and other ecological concerns. Despite these known drawbacks of hydropower, it remains a low-

[3] Throughout the discussion of the average numerical values obtained for each (sub)indicator and displayed on our graphs, "score" will refer to the arithmetic mean score.

carbon energy source, plentiful in certain geographical contexts, and an important part of the renewable energy mix.

- Natural Gas (score: 1.79/5) has the lowest score, indicating it is less sustainable in terms of carbon emissions. While it is cleaner than coal and oil, burning natural gas still releases significant amounts of carbon dioxide into the atmosphere. The low score reflects the fact that natural gas, though often promoted as a "bridge fuel" in the transition to low-carbon energy, is still a fossil fuel and contributes to GHG emissions. Its relatively low score underlines the need for a shift towards cleaner, more sustainable energy sources to meet global carbon reduction goals.

(I 1.2) - Land occupation

The **land occupation indicator** is used to assess the sustainability of energy technologies by quantifying the amount of land required to produce a certain amount of energy. It is particularly relevant in assessing renewable energy technologies like solar, wind, biomass, and hydropower, where land use can significantly impact environmental and social sustainability

The indicator measures the land occupation considering the entire lifecycle of each energy technology. It is usually expressed in m^2*year/MWh (**Land Occupation per Unit of Energy)**.

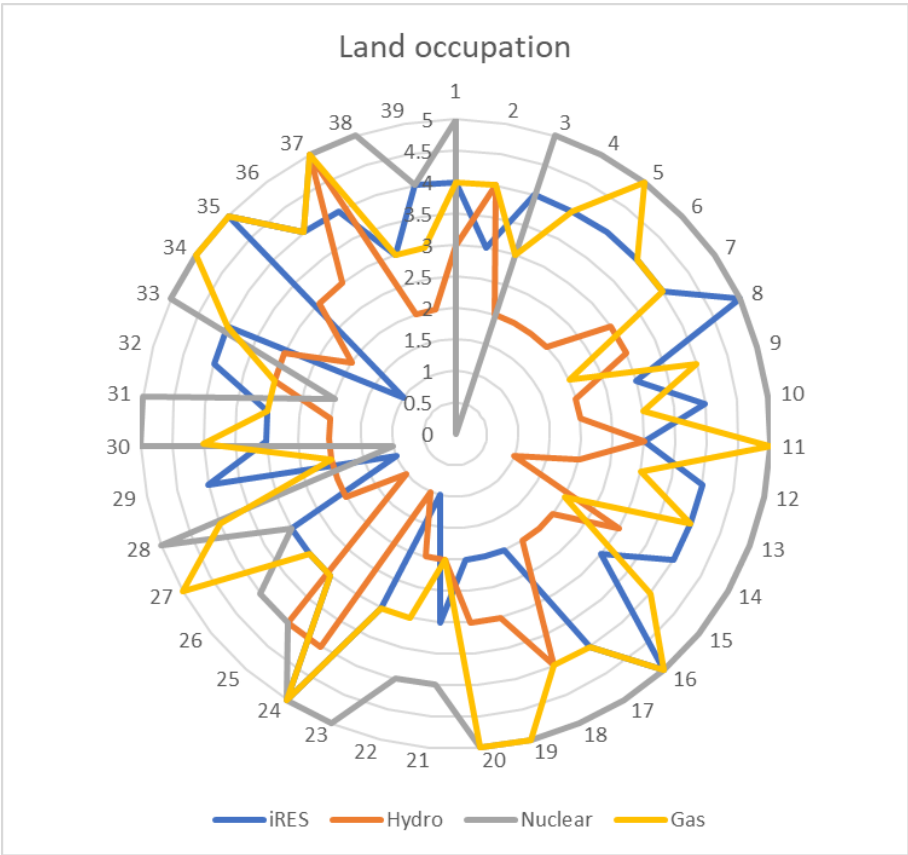


Fig. 4.1.2a, Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator I 1.2 – Land occupation, "radar" graph of data from the 40 respondents

The assessment on the sustainability performances for this indicator indicates judgments on how different energy sources impact land occupation. The possible scores range from 1 to 5, with higher scores indicating a *lower land occupation* and therefore better sustainability. The results accumulated from the respondents are presented in Fig. 4.1.2a & b.

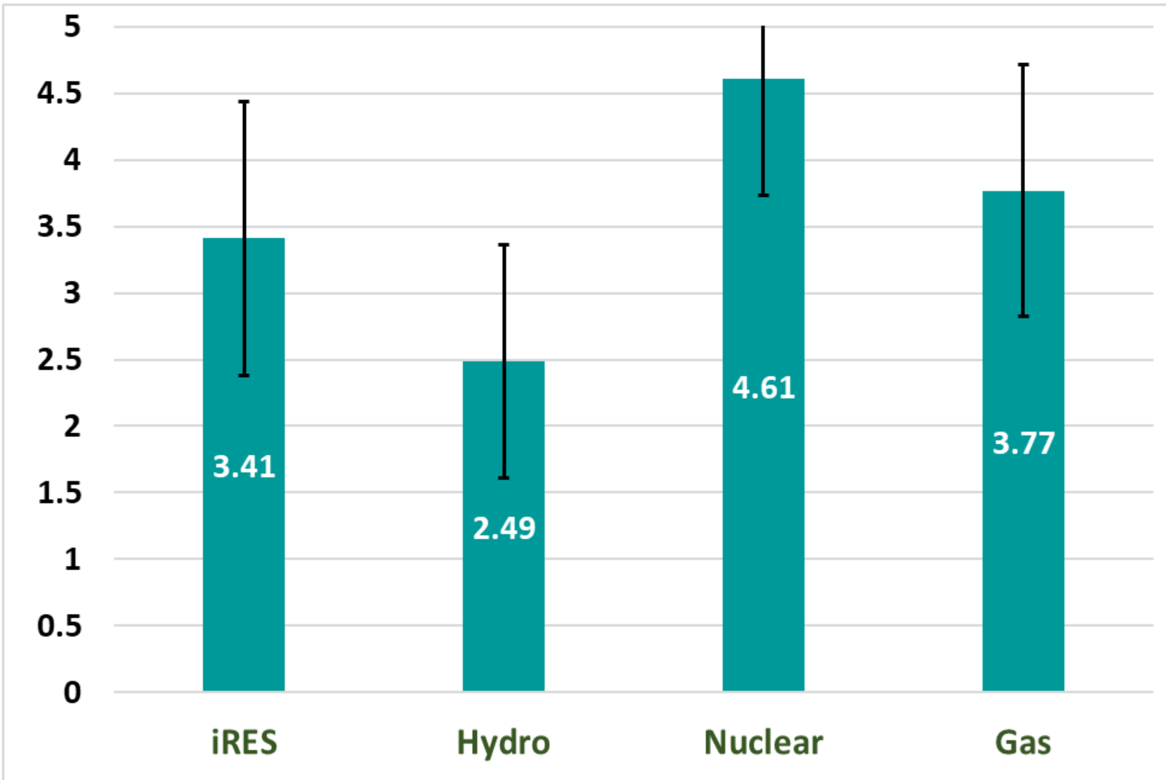


Fig. 4.1.2b Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator I 1.2 – Land occupation

- Nuclear technology emerged as the top performer, receiving the highest mean score of 4.61 out of 5. This result suggests the efficiency of nuclear power in terms of land use, as it typically requires a much smaller land footprint compared to other energy sources while generating large amounts of continuous, reliable energy.
- Natural gas followed closely with a score of 3.77. Like nuclear, gas-powered plants are known for their relatively compact land requirements, especially when considering their high energy output relative to the space they occupy. The moderate score indicates a recognition of the use of the land considering the entire life cycle of the technology, like extraction, processing, transport, etc.
- Intermittent renewable energy sources (iRES) scored 3.41. While these technologies are crucial for the transition to sustainable energy, their lower score reflects the considerable land area they require to generate energy at scale. The intermittent nature of these sources also means that large land areas must be dedicated to compensate for variability in energy production.
- On the other end of the spectrum, hydropower received the lowest score of 2.49. Despite being a renewable source of energy, hydropower often involves significant land use due to the need for large reservoirs and dams, which can lead to substantial environmental and social impacts, such as ecosystem disruption and displacement of local communities.

The results highlight the trade-offs between energy output and land occupation across different technologies. Nuclear and gas technologies may be seen as more favorable for their efficient land use, while hydropower and intermittent renewables face challenges due to their larger land requirements, despite their environmental benefits.

(I 1.3) EROI (Energy Return on Investment)

Energy return on investment (EROI) is defined as the ratio between the energy delivered by a particular fuel or technology to the society and the input energy (invested in capturing and delivering this energy to the society). EROI is a measure of the "profit" obtained in terms of energy by investing an amount of energy and obtaining a final usable energy. Sometimes it is referred as "energy returned on energy invested".

When EROI is less than 1, the process is a net consumer of energy, therefore it can no longer to be used as a source of energy. Generally, a value at least 3 is necessary to consider market viability for a fuel or energy technology.

The results of the assessment, aggregated in an averaged score, considering all the answers from the respondents, are presented in Fig. 4.1.3. The scale used is 1 to 5, 1 for minimum performance, and 5 for maximum performance (*higher EROI*).

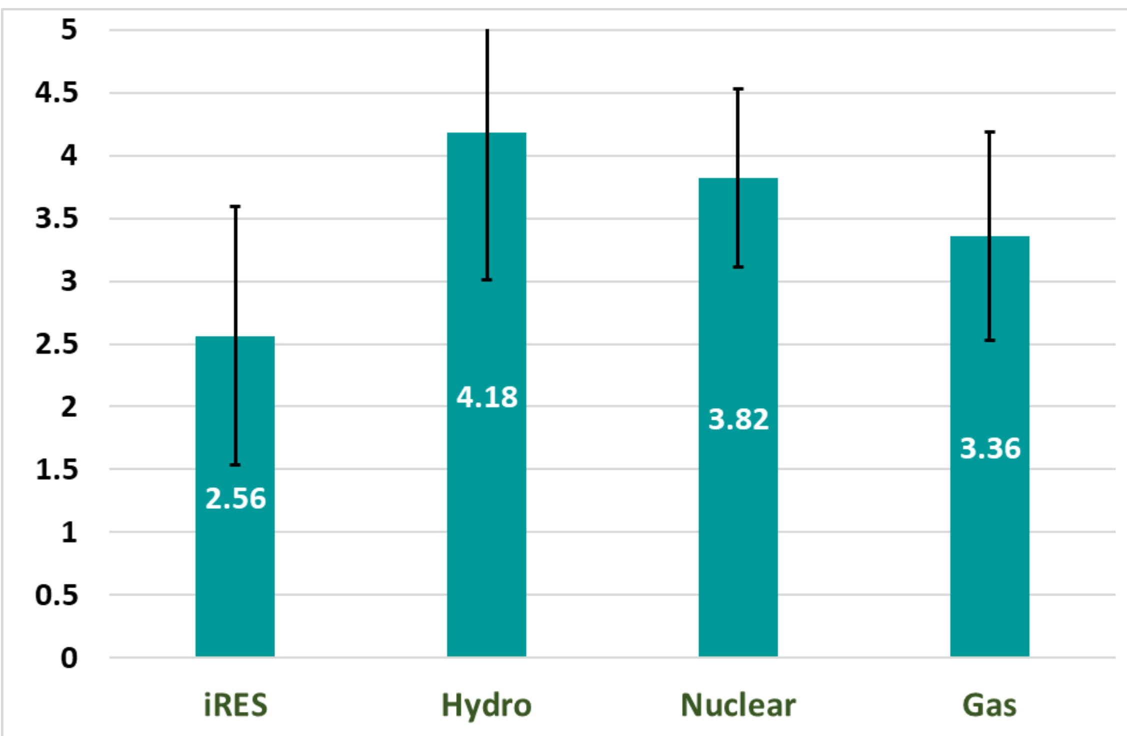


Fig. 4.1.3 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator I 1.3 – Energy Return on Investment

- Hydropower emerged as the top performer in the assessment, with a score of 4.18 out of 5. This high mean score reflects hydropower's excellent EROI, often estimated in literature to be between 10 and 30. The efficiency of hydropower comes from its ability to convert a high percentage of the potential energy stored in water into usable electricity with minimal energy input beyond the initial infrastructure setup. The high EROI of hydropower makes it a highly sustainable energy source from an energy efficiency perspective. However, while the survey score highlights its strong performance in terms of energy return, it is important to balance this with considerations of environmental and social impacts, such as ecosystem disruption and land use changes. These factors, though not directly related to EROI, are critical in the broader assessment of hydropower's overall sustainability.

- Nuclear energy achieved a strong score of 3.82, reflecting its generally high EROI, which ranges in literature from 10 to 15. Nuclear power is known for its ability to produce large amounts of continuous and reliable energy with relatively low operational energy inputs. The high EROI of nuclear energy supports its role as a key component of the global energy mix, particularly in countries looking to reduce carbon emissions while maintaining energy security The slightly lower score compared to hydropower could be attributed to the high upfront energy costs associated with constructing nuclear plants, including the energy-intensive processes of mining, fuel processing, and waste management. Despite these challenges, nuclear energy remains one of the most efficient options available, providing a significant net energy gain over its operational lifetime.
- Natural gas scored 3.36, reflecting its moderate to high EROI, which typically ranges (in the literature) from 7 to 10. This score indicates that while natural gas is an efficient energy source, it is not as strong in terms of net energy gain as hydropower or nuclear energy. Natural gas is widely used due to its relatively low cost and established infrastructure, which contribute to its favorable EROI. However, the score also suggests that natural gas faces challenges in comparison to technologies with higher EROI, particularly in the context of a global shift toward low-carbon energy sources. The extraction, transportation, and conversion processes for natural gas are energy-intensive, which can limit its overall efficiency. Additionally, the environmental impact of methane emissions and the finite nature of fossil fuel resources may have influenced the perception of natural gas in this assessment.
- Intermittent renewable energy sources (iRES), which include solar and wind, received the lowest score of 2.56. This result reflects the challenges associated with the EROI of these technologies, which typically ranges in literature from 3 to 10, depending on factors like location, technology type, and scale. The relatively low EROI of iRES is primarily due to the intermittent nature of these energy sources, which requires substantial investments in energy storage, grid management, and backup systems to ensure a reliable energy supply. The lower score highlights the current limitations of iRES in terms of net energy gain, particularly when compared to more established technologies like hydropower and nuclear energy. However, it is important to recognize that iRES are still essential for the transition to a sustainable energy future, despite their lower EROI. Ongoing advancements in technology and infrastructure are expected to improve the efficiency and EROI of iRES over time, making them more competitive in the long term.

The results offer a nuanced view of energy technologies from the perspective of EROI. Hydropower and nuclear energy stand out as the most efficient in terms of net energy gain, with hydropower taking the lead. Natural gas also performs well, though it lags behind in comparison to these higher EROI technologies. Intermittent renewable energy sources, while crucial for sustainability, currently face challenges in terms of EROI, as reflected in their lower score.

These findings underscore the importance of considering EROI alongside other factors, such as environmental impact, technological maturity, and economic feasibility, when assessing the sustainability of energy technologies. As the global energy landscape continues to evolve, improving the EROI of renewable technologies and balancing efficiency with environmental and social considerations will be key to achieving a sustainable energy future.

(I 1.4) Impact on resources, (S_i 1.4.1) Operational water consumption

The indicator is defined as the amount of water consumed by a technology, usually quantified in m^3 of water consumed for 1 kWh of electricity produced. The results of the assessment, aggregated in an averaged score, considering all the answers from the respondents, are presented in Fig. 4.1.4. The used scale is 1 to 5, 1 for minimum performance, and 5 for maximum performance (*lower consumption*).

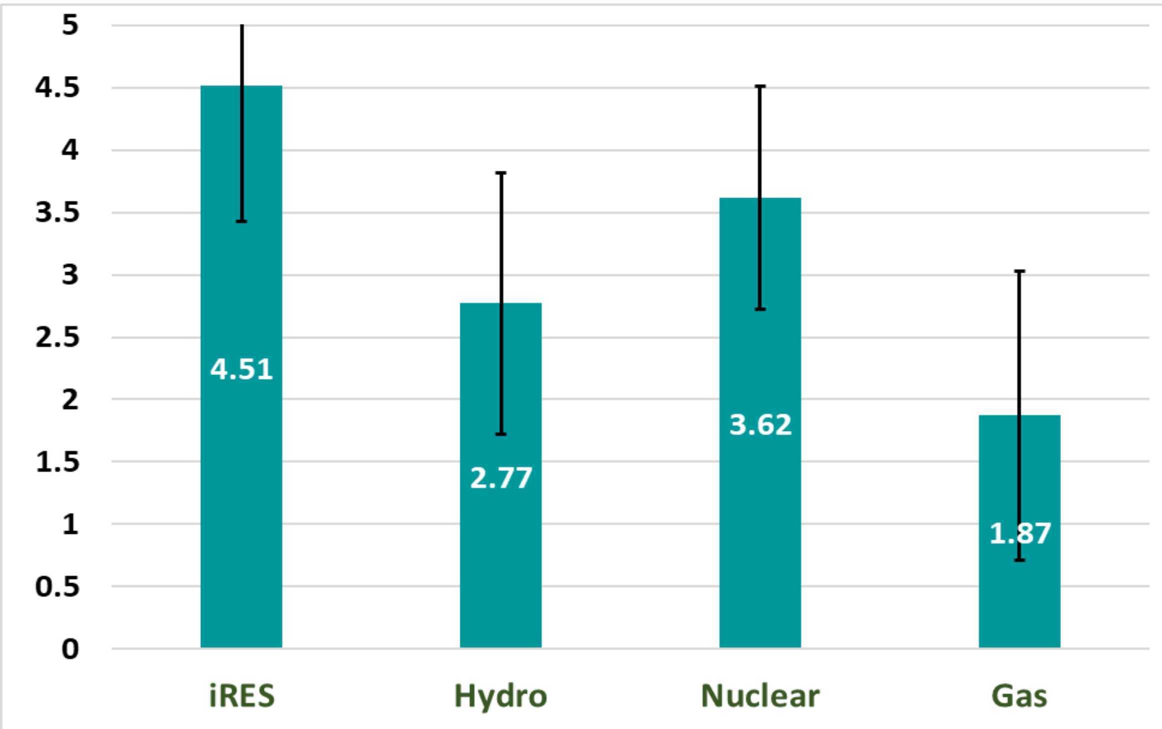


Fig. 4.1.4 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator I 1.4 Impact on resources – S_i 1.4.1 Performance in operational water consumption

The assessment reveals that iRES are the most sustainable option in terms of water consumption, followed by nuclear, hydropower, and natural gas.

- Intermittent renewables (score: 4.51/5) include solar and wind energy, which rely on natural, non-depleting sources like sunlight and wind. These technologies typically have minimal water requirements during operation, primarily for cleaning solar panels or cooling in specific wind turbine designs. The high score reflects the low operational water consumption associated with these technologies, making them highly sustainable in terms of water usage. This is a significant advantage in regions facing water scarcity.
- Nuclear (score: 3.62/5) power plants require significant amounts of water for cooling purposes. Water is often drawn from nearby sources, and although much of it is returned, the process can lead to thermal pollution and reduced water quality. The score suggests that, in the opinion of the participants, nuclear power has a moderate impact on water resources. While the water

consumption is notable, it is lower than in some fossil fuel plants, and the use of advanced cooling technologies can mitigate some of the impacts.

- Hydropower (score: 2.77/5) relies on the flow of water to generate electricity. Although it does not consume water in the traditional sense, it significantly impacts water resources by altering natural water flow, creating reservoirs, and potentially affecting ecosystems. The moderate score resulted from the answers of the respondents indicates that while hydropower is a renewable energy source, its impact on water resources is substantial. The creation of dams can lead to changes in water availability downstream, affecting both ecosystems and human communities.

- Natural gas (score: 1.87/5), especially combined cycle plants, require substantial amounts of water for cooling. The water consumption is high, and the extraction of natural gas through hydraulic fracturing (fracking) can also severely impact water resources. The low score highlights the significant water resource impact associated with natural gas operations. Both operational water consumption and the broader environmental impacts of water use in extraction contribute to its poor sustainability performance.

Given the emergence of critical concerns over water availability in many world regions, prioritizing technologies with lower water impacts will be crucial in the transition to more sustainable energy systems.

(I 1.4) Impact on resources, (S_i 1.4.2) Abiotic resources depletion

Abiotic resources depletion is defined by the Abiotic Depletion Potential (ADP), a metric used to assess the potential environmental impact of resource depletion in non-living natural resources. It is a way to quantify the depletion of non-renewable resources in a manner that considers the finite nature of these resources and the environmental consequences associated with their extraction and use.

ADP is typically expressed in units such as person-years or kilogram-years and is used to estimate how many years it would take for a particular resource to be depleted completely, taking into account factors like the amount of resource available, the rate of extraction, and the environmental impact associated with that extraction.

The indicator is given in kg·Sb eq per kWh of energy production. It quantifies the potential depletion of various abiotic resources, expressed in kilograms of antimony equivalents, that would result from generating one kilowatt-hour of electricity. It provides a way to assess the environmental impact of electricity generation concerning the depletion of non-renewable resources. This unit is part of the broader effort to assess the sustainability and environmental consequences of energy production methods.

The assessment on the sustainability performances for this indicator examines how different energy sources contribute to the depletion of non-living (abiotic) natural resources, such as minerals, during their lifecycle. The possible scores range from 1 to 5, with higher scores indicating a *lower impact on resource depletion* and therefore better sustainability. The averaged scores, resulted from the answers of the respondents, are presented in Fig. 4.1.5.

- Hydropower (score: 4.47/5) uses the kinetic energy of flowing water to generate electricity, relying primarily on the construction of dams and water reservoirs. The materials required for building dams and turbines include concrete, steel, and other construction materials, but once constructed, the ongoing depletion of abiotic resources is minimal. The high score indicates that hydropower has a relatively low impact on abiotic resource depletion. Once the infrastructure is built, the operation of hydropower plants requires little in the way of additional non-living natural resources, making it a sustainable option in this regard.

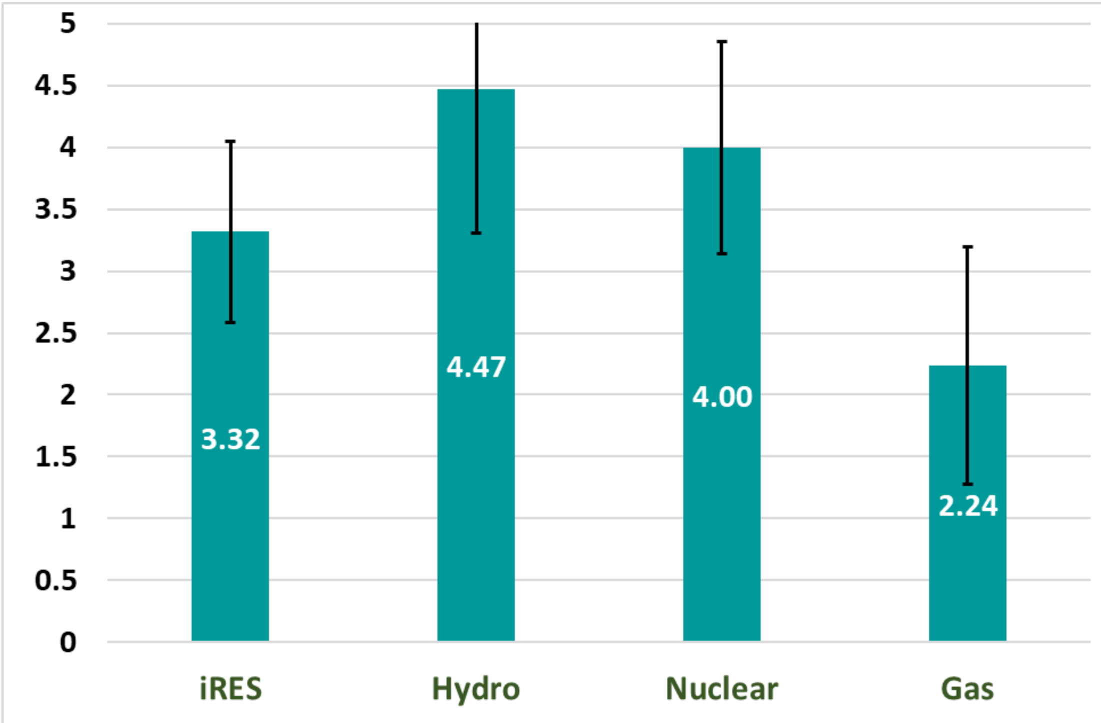


Fig. 4.1.5 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator I 1.4 Impact on resources – S_i 1.4.2 – Performance in Abiotic Resources Depletion

- Nuclear power (score: 4.00/5) relies on uranium as a fuel source, which is a finite abiotic resource. The construction of nuclear plants also requires significant amounts of concrete, steel, and other materials. However, the energy density of uranium is very high, meaning that a small amount of fuel can produce a large amount of energy. The score suggests that while nuclear power does deplete abiotic resources (notably uranium), its impact is somewhat mitigated by the efficiency of the fuel and the long operational life of nuclear plants. Thus, its overall depletion impact is lower compared to fossil fuels but higher than renewable sources like hydro.
- Intermittent renewables (score: 3.32/5) depend on renewable sources but require significant amounts of abiotic resources like metals (copper, aluminum, rare earth elements) for the production of solar panels, wind turbines, and batteries. The moderate score reflects the fact that while these technologies are environmentally friendly in terms of emissions, their manufacturing processes are resource-intensive. Mining and processing the required materials can have a substantial environmental impact, contributing to abiotic resource depletion.
- Natural gas (score: 2.24/5) is a fossil fuel, which means that its extraction and use directly deplete finite abiotic resources. Additionally, the infrastructure for extraction, transportation, and power generation (e.g., pipelines, gas plants) requires significant amounts of other abiotic resources like metals and concrete. The low score indicates that natural gas has a low sustainability performance concerning abiotic resource depletion. The extraction process, combined with the use of finite resources, makes it one of the least sustainable options in this category.

The assessment suggests that hydropower and nuclear power are relatively sustainable in terms of abiotic resource depletion, primarily due to their efficiency and the longevity of their infrastructure compared to the energy they produce. Intermittent renewables have a moderate impact, reflecting the significant resource requirements for manufacturing but balanced by the renewable nature of the energy they produce. Natural gas, with its reliance on fossil fuels and the significant infrastructure needed, scores the lowest, indicating a high impact on the depletion of abiotic resources.

In the context of sustainability, these results underline the importance of considering resource use efficiency and the life cycle impact of energy technologies. While renewables like solar and wind have many advantages, their reliance on certain critical materials needs to be managed carefully to ensure long-term sustainability.

(I 1.4) Impact on resources, (S_i 1.4.3) Depletion of fossil fuels

The sustainability indicator "Impact on Resources, Depletion of Fossil Fuels" measures the extent to which energy technologies contribute to the consumption and eventual depletion of non-renewable fossil fuel resources, such as coal, oil, and natural gas. This indicator assesses the reliance of different energy sources on fossil fuels and their sustainability in terms of resource availability over time. The component aspects of the indicator are: (1) fossil fuel dependency (how much a particular energy technology depends on fossil fuels for its operation or in its lifecycle, (2) resource depletion rate (assesses the rate at which fossil fuels are consumed by the technology, contributing to the exhaustion of these finite resources), (3) sustainability (lower scores on this indicator reflect a higher impact on fossil fuel depletion, indicating less sustainability).

The assessment on the sustainability performances for this indicator examines how different energy sources contribute to the depletion of fossil fuels during their lifecycle. The possible scores range from 1 to 5, with higher scores indicating a *lower impact on fossil fuel depletion* and thus better sustainability. The results are presented in Fig. 4.1.6.

- Intermittent renewables (score: 4.29/5), including solar and wind energy, do not rely on fossil fuels for electricity generation. They harness natural energy sources like sunlight and wind, which are abundant and renewable. The only fossil fuel-related impact may come indirectly from the manufacturing, transportation, and installation of equipment, such as solar panels and wind turbines. The high score reflects the minimal reliance on fossil fuels for operation, making intermittent renewables one of the most sustainable options regarding fossil fuel depletion. The slight reduction from a perfect score might account for the fossil fuel usage involved in the production and deployment of renewable energy infrastructure.
- Hydropower (score: 4.23/5) generates electricity by harnessing the energy of moving water, typically requiring no fossil fuels during operation. The primary fossil fuel impact arises during the construction of dams and associated infrastructure. The score indicates that hydropower is also highly sustainable concerning fossil fuel depletion. Its score is slightly lower than intermittent renewables, potentially due to the significant initial use of resources and energy in building the infrastructure, but overall, it has a low ongoing fossil fuel requirement.
- Nuclear power (score: 3.23/5) primarily relies on uranium, not fossil fuels, for energy production. However, the construction, operation, and maintenance of nuclear plants, as well as the uranium mining and fuel processing, can involve some use of fossil fuels, particularly in the transportation and processing stages. The moderate score suggests that while nuclear power does not directly consume fossil fuels for electricity generation, its lifecycle still involves some fossil fuel usage.

The extraction and processing of uranium, as well as the construction of nuclear plants, contribute to this impact.

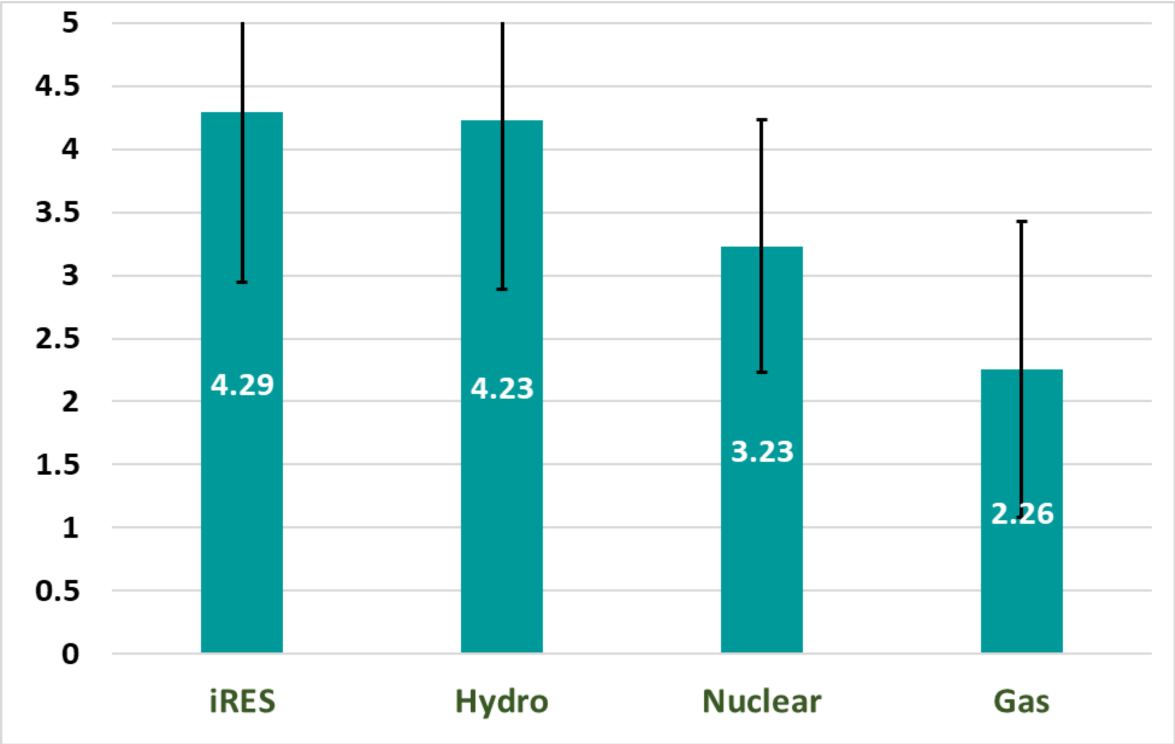


Fig. 4.1.6 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator I 1.4 Impact on resources – S_i 1.4.3 – Performance in Fossil fuel depletion

- Natural gas (score: 2.26/5) is a fossil fuel, and its extraction, processing, and burning for energy directly contribute to fossil fuel depletion. While it is often described as a "bridge fuel" due to its lower emissions compared to coal or oil, its reliance on finite fossil fuel reserves is significant. Although the mean is not highly consensual (spread of judgments or error bar of approximately 2.5 points), the low mean score indicates that natural gas is not viewed as sustainable concerning fossil fuel depletion. Its direct use of a finite resource means that continued reliance on natural gas will exacerbate the depletion of fossil fuel reserves, making it one of the least sustainable energy sources in this category.

The assessment shows that intermittent renewables and hydropower are the most sustainable energy sources in terms of fossil fuel depletion, both scoring above 4. These energy sources rely minimally on fossil fuels, primarily during the infrastructure development phase, and are highly sustainable once operational. Nuclear power scores moderately due to some indirect fossil fuel use during its lifecycle, mainly related to uranium mining, plant construction, and maintenance. Natural gas scores the lowest, reflecting its direct and significant contribution to fossil fuel depletion.

These results highlight the importance of transitioning to energy sources that minimize or eliminate fossil fuel use. Intermittent renewables and hydropower emerge as the most sustainable options in this regard, whereas natural gas, despite being cleaner than other fossil fuels, still represents a significant strain on finite fossil fuel resources.

(I 1.4) Impact on resources, (S_i 1.4.4) Excessive use of resources useful for sustaining life

Overconsumption means consuming resources that cannot be replenished or that cannot sustain themselves at the rate we are consuming them. Ecosystems are unable to cope with excessive resource extraction, resulting in biodiversity loss and the deterioration of the natural world.

The excessive use of life-sustaining resources was analyzed, qualitatively, from the perspective of the impact on water, air and soil, the three natural resources without which we cannot live.

The assessment on the sustainability performances for this indicator examines how different energy sources impact resources that are essential for sustaining life, such as water, land, and clean air. The possible scores range from 1 to 5, with higher scores indicating a *lower impact on these critical resources* and thus a better sustainability. The results are presented in Fig. 4.1.7.

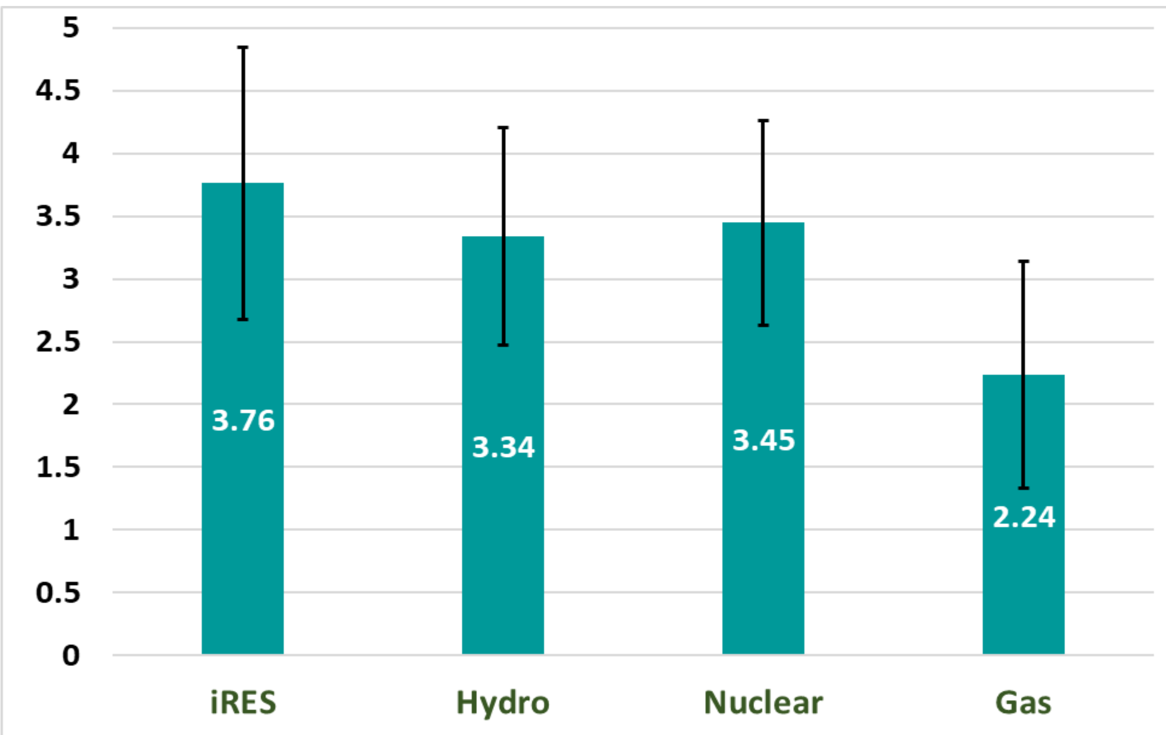


Fig. 4.1.7 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator I 1.4, S_i 1.4.4 – Excessive use of life sustaining resources

- Intermittent renewables (score: 3.76/5) generally have a low impact on life-sustaining resources once operational. However, the slightly higher variability of judgments here (longer error bar) may reflect the fact that the manufacturing and deployment of solar panels and wind turbines require substantial amounts of materials, some of which are rare and involve environmentally intensive extraction processes. Some raters may be more sensitive to, or have more life-cycle knowledge about these aspects. Additionally, large-scale solar farms and wind farms require significant land areas, potentially impacting habitats, and agricultural land. The score of 3.76 reflects that while intermittent renewables are far less harmful compared to fossil fuels, they do involve the use of materials and land that are crucial for sustaining life. The extraction of rare materials and the conversion of land for renewable energy installations are the primary concerns, although these impacts are generally less severe than those associated with conventional energy sources.

- Nuclear power (score: 3.45/5) has a moderate impact on resources vital for life. The construction and operation of nuclear plants require significant land and water, particularly for cooling purposes. Water use in nuclear power plants can affect local water bodies, potentially leading to thermal pollution and affecting aquatic life. Additionally, while nuclear plants occupy some areas, they produce significant amounts of energy, reducing the overall land use compared to the amount of energy generated. The score of 3.45 suggests that nuclear power does involve a considerable use of life-sustaining resources. The risks associated with radioactive waste management and potential accidents, though rare, also contribute to the impact on resources critical for human and ecological health.
- Hydropower (score: 3.34/5) has a notable impact on life-sustaining resources, primarily due to its reliance on water. The construction of dams alters river ecosystems, affects water availability downstream, and can lead to the displacement of local communities. Large reservoirs also submerge vast areas of land, potentially affecting agricultural land and natural habitats. Additionally, changes in water flow can impact fish populations and other aquatic life, disrupting ecosystems that are vital for sustaining life.
- Natural Gas (score: 2.24/5) has a substantial negative impact on resources that are essential for life. The extraction process, particularly through hydraulic fracturing (fracking), can lead to significant water use and contamination, affecting drinking water supplies and ecosystems. The land use for drilling and infrastructure development can disrupt local ecosystems, and the emissions from burning natural gas contribute to air pollution, affecting air quality and public health. The low score of 2.24 indicates that natural gas is highly unsustainable when it comes to the excessive use of life-sustaining resources. Its extraction and use not only deplete these resources but also degrade their quality, making it one of the most detrimental energy sources in this regard.

In terms of the excessive use of resources that are essential for life, intermittent renewables and nuclear power emerge as the more sustainable options, though they are not without their own impacts on land, water, and material use. Hydropower has a slightly higher impact due to its significant alteration of water systems and land use. Natural gas, with its extensive use of water, land disruption, and air pollution, scores the lowest, highlighting its substantial negative impact on life-sustaining resources.

These findings emphasize the importance of minimizing the environmental footprint of energy production, particularly in terms of resources that are critical for human and ecological health. While renewable energy sources are generally better in this respect, careful consideration must still be given to their resource use to ensure a truly sustainable energy future. These results underscore the importance of considering the broader environmental and ecological impacts when assessing the sustainability of energy sources. While renewables and nuclear power offer benefits in terms of emissions, their impacts on resources essential for life must be carefully managed to ensure a truly sustainable energy future.

(I 1.4) Impact on resources, (S_i 1.4.5) Exhausting of rare resources

Rare elements, often referred to as rare earth elements (REEs), are a group of 17 chemically similar elements in the periodic table. These elements are crucial components in various advanced technologies.

The assessment on the sustainability performances for this indicator examines how different energy sources contribute to the depletion of rare and finite materials during their lifecycle. These materials can include rare earth elements, specific metals, and other non-renewable resources that are crucial for technology and industry. The possible scores range from 1 to 5, with higher scores indicating a *lower impact on the depletion of rare resources* and thus better sustainability. The results are presented in Fig. 4.1.8.

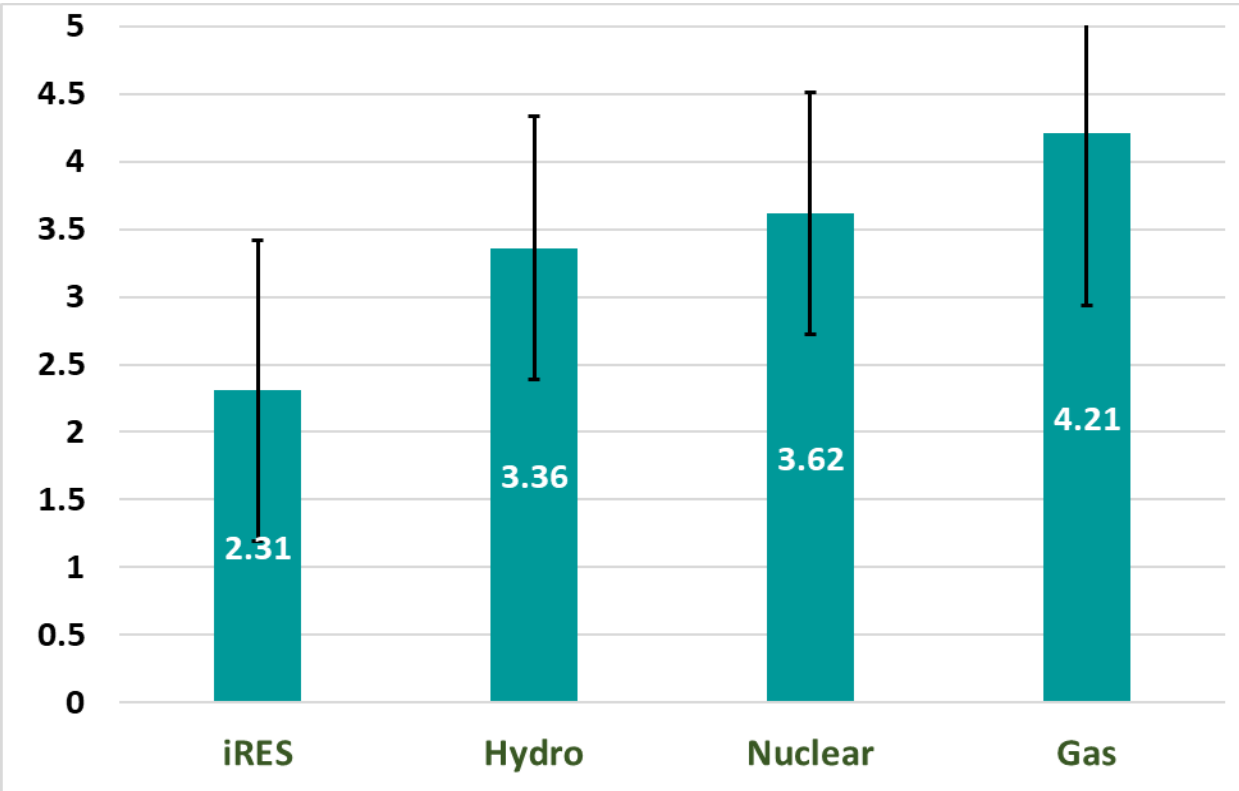


Fig. 4.1.8 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator I 1.4, S_i 1.4.5 – Exhausting of rare resources

The assessment shows that natural gas has the least impact on the depletion of rare resources, given its minimal reliance on scarce materials. Nuclear power and hydropower follow, with moderate impacts due to their use of some specialized but not typically rare materials. Intermittent renewables, despite their environmental benefits in other areas, score the lowest in this category due to their heavy dependence on rare earth elements and other limited materials.

- Natural gas (score: 4.21/5) extraction and usage primarily involve common materials such as steel, concrete, and basic infrastructure, which are not considered rare resources. The process does not rely heavily on rare earth elements or other scarce materials. Thus, its impact on the depletion of rare resources is relatively low. The high score of 4.21 reflects that natural gas operations have minimal reliance on rare materials, making it relatively sustainable in terms of exhausting rare resources.
- Nuclear power (score: 3.62/5) requires certain rare materials, such as specific alloys for reactor components and rare isotopes like uranium-235 for fuel. However, uranium, while finite, is not

considered rare in the same sense as some critical metals used in other technologies. The nuclear industry also makes use of advanced materials with specific properties, but these are not typically among the rarest elements. The score of 3.62 indicates a moderate impact on the exhaustion of rare resources. While nuclear power does require some materials that are limited in supply, it is generally less dependent on rare earth elements compared to technologies like those used in renewable energy. The relatively lower use of rare materials gives nuclear power a fairly sustainable profile in this regard.

- Hydropower (score: 3.36/5) primarily involves the use of common materials such as concrete, steel, and mechanical components for turbines and dams. These materials are not considered rare, and the overall reliance on scarce resources in hydropower projects is minimal. The score of 3.36 suggests that the respondents consider hydropower has a low to moderate impact on the exhaustion of rare resources.
- Intermittent renewables (score: 2.31/5), particularly wind and solar energy, heavily rely on rare materials. For instance, solar panels require rare earth elements like tellurium, indium, and gallium, while wind turbines use neodymium and dysprosium for their magnets. These materials are limited in supply and often concentrated in a few geographical locations, making them more susceptible to exhaustion. The low mean score (although somewhat less consensual than others on this graph) reflects the significant reliance of renewable technologies on rare resources. While these energy sources are sustainable in terms of emissions and operational impacts, their dependence on scarce materials poses a challenge for long-term sustainability. The extraction and processing of these rare elements can also have significant environmental and geopolitical implications.

These results highlight a critical aspect of sustainability: while renewables are essential for reducing carbon emissions, their reliance on rare resources introduces new challenges. The sustainability of energy systems must consider not only operational emissions and resource use but also the long-term availability and environmental impact of the materials required for these technologies. This underscores the importance of developing more sustainable supply chains, as well as recycling technologies, and of finding alternative materials for renewable energy systems.

(I 1.5) Potential material recyclability

The "Potential of Material Recyclability" is a sustainability indicator that measures the extent to which materials used in energy technologies can be recovered and reused at the end of their lifecycle. This indicator examines the recyclability of components and materials involved in the construction, operation, and decommissioning phases of energy infrastructure.

High recyclability contributes to resource efficiency, reduces environmental impact by minimizing waste, and supports the transition to a circular economy. By assessing this potential, decision-makers can prioritize technologies that not only generate low emissions during operation but also minimize their long-term environmental footprint.

The assessment on the sustainability performances for this indicator examines how different energy sources contribute to the avoidance (by recycling) of the depletion of finite materials during their lifecycle. The possible scores range from 1 to 5, with higher scores indicating a *lower impact on the depletion of rare resources* and thus better sustainability. The results are presented in Fig. 4.1.9.

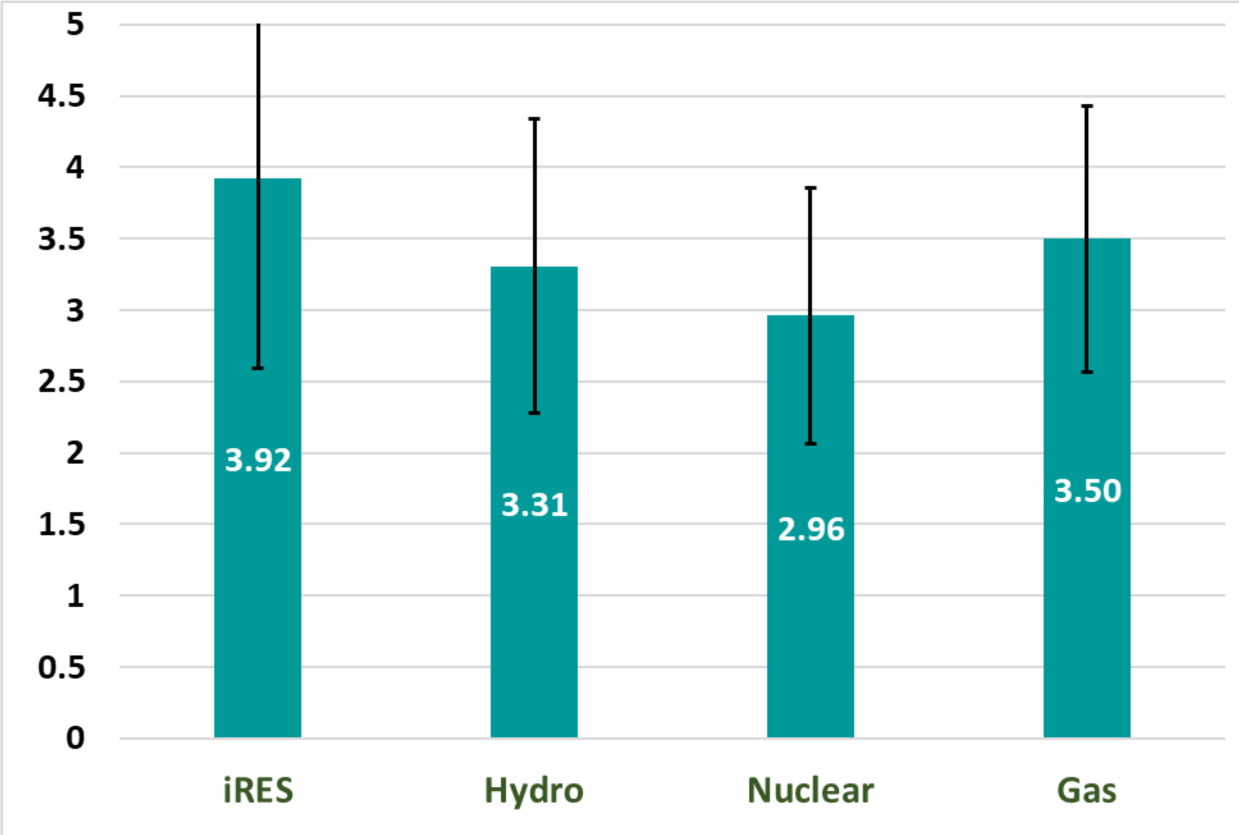


Fig. 4.1.9 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator I 1.5 – Potential material recyclability

The assessment of potential material recyclability shows that intermittent renewables lead with a high score of 3.92, reflecting their strong recyclability profile, particularly with ongoing advancements in technology. Natural gas follows with a score of 3.50, indicating a moderate recyclability potential, especially for metal components. Hydropower scores 3.31, reflecting a good potential for recycling metals but facing challenges with concrete structures. Nuclear power scores the lowest at 2.96, primarily due to the difficulties in recycling materials that may be contaminated with radioactivity.

- Intermittent renewables (Score: 3.92/5) achieve the highest mean score of 3.92, indicating (despite some dissensus) a strong potential for material recyclability. These technologies primarily use materials like metals (steel, aluminum, copper) and glass, which are highly recyclable. Advances in technology are also improving the recyclability of solar panels and wind turbine blades, which traditionally posed challenges due to their composite materials. The result underscores the significant recyclability potential of materials used in renewable energy technologies. As the industry continues to innovate, the ability to recycle these materials efficiently not only enhances the sustainability of renewables but also reduces waste and the demand for virgin resources.

- Natural gas (Score: 3.50/5) scores 3.50, reflecting a moderate potential for material recyclability. The infrastructure for natural gas, including pipelines, compressors, and power plants, is primarily constructed from metals that can be recycled. However, some components, particularly those exposed to high pressures and temperatures, may be less recyclable due to material degradation over time. The score suggests that the natural gas sector has a reasonable potential for material recyclability, particularly for metal components. However, challenges remain in recycling certain specialized materials, and there is room for improvement in managing the end-of-life phase of these infrastructures to enhance overall recyclability.

- Hydropower (Score: 3.31/5) scores 3.31, indicating a good but not exceptional potential for material recyclability. The construction of hydropower plants involves large amounts of concrete and metals, which have varying levels of recyclability. While metals used in turbines and generators are highly recyclable, the recycling of concrete structures, such as dams, is more challenging and less efficient. The score of 3.31 reflects the mixed recyclability profile of hydropower materials. While key components are recyclable, the large-scale use of concrete poses significant challenges, particularly in terms of energy and cost. Improvements in recycling technologies for concrete and the sustainable decommissioning of hydropower plants could enhance this score.

- Nuclear power (Score: 2.96/5) has the lowest score for potential material recyclability at 2.96. While many materials used in nuclear plants, such as metals in reactors and cooling systems, are technically recyclable, the presence of radioactive contamination complicates the recycling process. The decommissioning of nuclear plants involves strict regulations and safety protocols, which often limit the extent to which materials can be recycled. The score highlights the challenges associated with recycling materials in the nuclear sector. Radioactive contamination poses significant barriers, making the recycling process more complex, costly, and less feasible. Enhancing decontamination processes and developing new methods for safely recycling nuclear materials could improve this score in the future.

These results highlight the importance of enhancing recycling processes across all energy sectors to improve sustainability. While intermittent renewables show the most promise, natural gas and hydropower also have substantial potential, particularly with innovations in material recycling. Nuclear power presents the greatest challenge, emphasizing the need for continued research and development in decontamination and recycling technologies.

(I 1.6) Emissions (other than C) (S_i 1.6.1) NOx and SO_2 emissions

The Sulfur Oxides (SO_2) and Nitrogen Oxides (NO_x) are the major air pollutants, being the most common indicators used in lifecycle assessments in the literature for comparing chemical pollution and its potential impacts on water ecosystems, in relation to air pollution, soil quality and terrestrial ecosystems.

The assessment on the sustainability performances for this indicator examines how different energy sources contribute to emissions of nitrogen oxides (NOx) and sulfur dioxide (SO_2), both of which are harmful pollutants that can contribute to acid rain, respiratory problems, and environmental degradation. The possible scores range from 1 to 5, with higher scores indicating *lower emissions of these pollutants* and therefore better sustainability. The results are presented in Fig. 4.1.10.

The assessment indicates that hydropower and nuclear power are viewed as the most sustainable in terms of NOx and SO_2 emissions, with scores close to 4. These energy sources do not produce these harmful pollutants during operation, making them highly favorable options from an air quality perspective. Intermittent renewables also score well, reflecting their clean operational profiles but acknowledging some indirect emissions during their lifecycle. Natural gas, while cleaner than other fossil fuels, still produces significant NOx emissions, resulting in a lower score and highlighting its limitations in terms of sustainability concerning NOx and SO_2 emissions.

Nonetheless it should be noted that the error bars (standard deviation) displayed indicate relatively low consensus on ratings for all four technologies for this indicator. This result could potentially translate the complexity of the indicator, making the interpretation of background materials more difficult for the respondents. Unfamiliarity with these pollutants could also conceivably contribute to the comparatively higher variability among raters.

- Hydropower (score: 4.08/5) generates electricity by using the kinetic energy of flowing or falling water. Since it does not involve combustion, it does not directly produce NOx or SO2 emissions during operation. The primary environmental impact is related to the construction of dams and other infrastructure, which does not contribute significantly to NOx or SO_2 emissions. The high score of 4.08 indicates that hydropower has very low emissions of NOx and SO_2, making it one of the most sustainable options in this category. The slight reduction from a perfect score may account for emissions related to the construction phase and any indirect emissions from infrastructure development, but overall, hydropower is very clean in terms of NOx and SO_2 emissions.

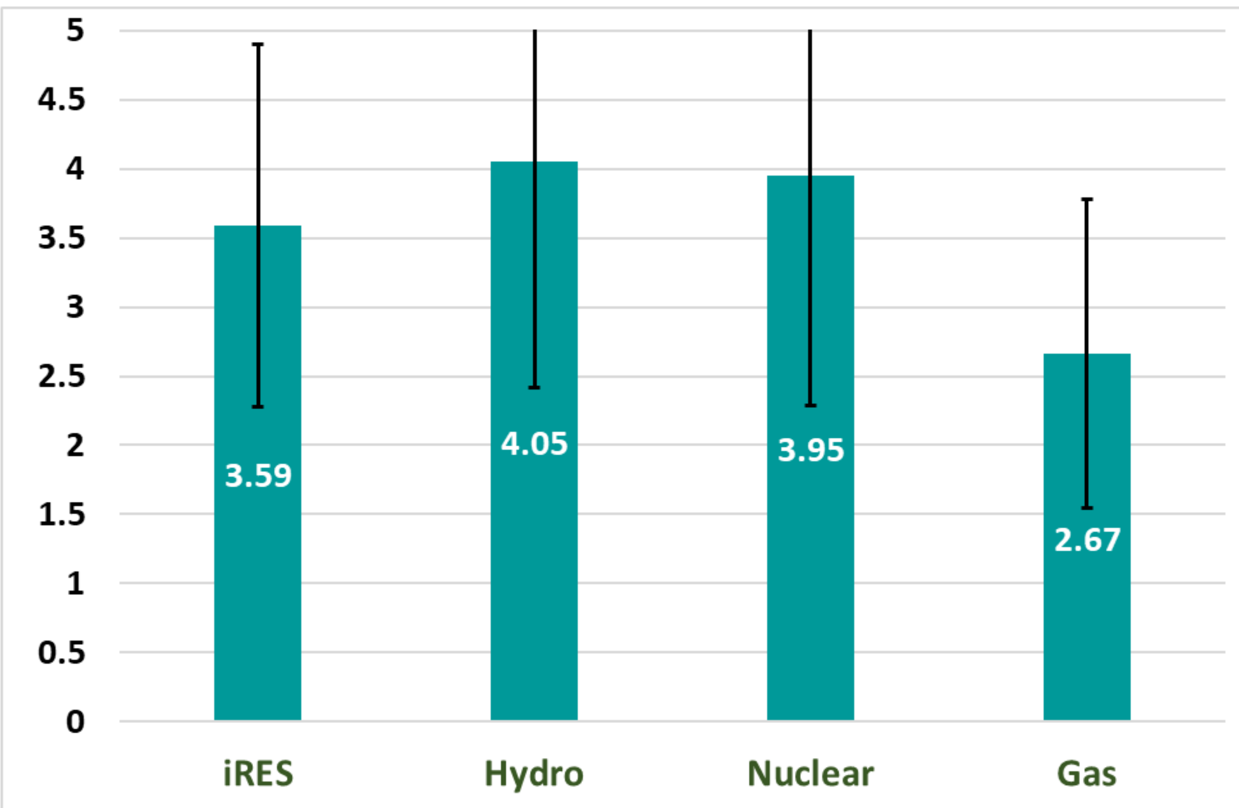


Fig. 4.1.10 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator I 1.6, Emissions (other than C) (S_i 1.6.1) NOx and SO_2 emissions

- Nuclear (score: 3.98/5) power plants generate electricity through nuclear fission without burning fossil fuels, so they do not emit NOx or SO_2 during operation. However, there may be minor emissions associated with the mining, processing, and transportation of nuclear fuel, as well as the construction of nuclear plants. The score of 3.98 reflects nuclear power's very low contribution to NOx and SO_2 emissions, similar to hydropower. The score indicates that while nuclear power has some indirect emissions, its operation is nearly free of NOx and SO_2, making it a highly sustainable option in this respect.

- Intermittent renewables (score: 3.63/5) do not involve combustion processes and therefore do not produce NOx or SO_2 emissions during operation. However, the manufacturing, transportation, and installation of solar panels, wind turbines, and associated infrastructure can lead to some emissions, depending on the energy sources used in these processes. The score of 3.63, resulted from the answers of the respondents, suggests that while the operation of renewable energy sources is clean with respect to NOx and SO_2 emissions, there are relevant associated emissions during the lifecycle of the technologies. These emissions are relatively low compared to fossil fuels, but they still prevent renewables from achieving a perfect score.

- Natural gas (score: 2.65/5) combustion emits NOx, though it produces less SO_2 compared to coal or oil due to its lower sulfur content. NOx emissions occur because of the high-temperature combustion process in power plants. Although natural gas is considered cleaner than other fossil fuels, it still contributes to air pollution through NOx emissions, which can lead to smog formation and health issues. The score of 2.65 indicates that natural gas has a moderate impact on NOx and SO_2 emissions. While it is cleaner than other fossil fuels like coal and oil, it still produces significant NOx emissions, which reduces its sustainability in this category. The lower score reflects these ongoing emissions and their environmental and health impacts.

These results emphasize the importance of considering not just carbon emissions but also other pollutants when assessing the environmental impact of different energy sources. Technologies that avoid combustion, such as hydropower, nuclear, and renewables, offer substantial benefits in reducing air pollution and protecting public health.

(I 1.6) Emissions (other than C) (S_i 1.6.2) Ozone depletion potential

Ozone Depletion Potential (ODP) represents the potential of depletion of the ozone layer due to the emissions of chlorofluorocarbon (CFC) compounds and chlorinated hydrocarbons. The ODP of the different contributing substances are converted to an equivalent quantity of CFC-11 and the indicator is expressed in units of µg CFC-11 eq/kWh.

The assessment on the sustainability performances for this indicator examines how different energy sources contribute to the depletion of the ozone layer. Ozone depletion is primarily caused by the release of certain chemicals, such as chlorofluorocarbons (CFCs) and halons, which break down ozone molecules in the stratosphere. The possible scores range from 1 to 5, with higher scores indicating a *lower potential for contributing to ozone depletion* and therefore better sustainability. The results are presented in Fig. 4.1.11.

The assessment shows that hydropower has the lowest ozone depletion potential among the considered energy sources, with a score of 3.33, followed closely by intermittent renewables and nuclear power. These energy sources have low direct emissions of ozone-depleting substances, but their overall lifecycle can involve processes that contribute slightly to ozone depletion. Natural gas scores the lowest, indicating a higher potential for ozone depletion due to the use of certain chemicals in its extraction, processing, and transportation.

- Hydropower (score: 3.33/5) generates electricity by utilizing the energy of flowing water and does not involve processes that directly release ozone-depleting substances. However, indirect emissions related to the manufacturing and maintenance of hydropower infrastructure may involve chemicals that have a not negligeable potential to contribute to ozone depletion. The score of 3.33 suggests that while hydropower has the better performance (in the -relatively highly dispersed- opinion of the respondents), there may be some indirect impacts associated with the production and maintenance of infrastructure. Overall, hydropower is considered a sustainable option with respect to ozone depletion, but the manufacturing processes involved might have some minor impacts.

- Intermittent renewables (score: 3.15/5) do not produce ozone-depleting emissions during their operation. However, the production, transportation, and disposal of renewable energy components, such as solar panels and wind turbines, might involve processes or materials that contribute slightly to ozone depletion. For example, some chemicals used in the manufacturing process may have ozone depletion potential. The score of 3.15 indicates that while the operational phase of renewable energy sources is free from ozone-depleting emissions, the lifecycle impacts related to the manufacturing and end-of-life disposal of components can have some effects on the ozone layer. This score reflects these indirect impacts, although they are relatively low compared to conventional energy sources.

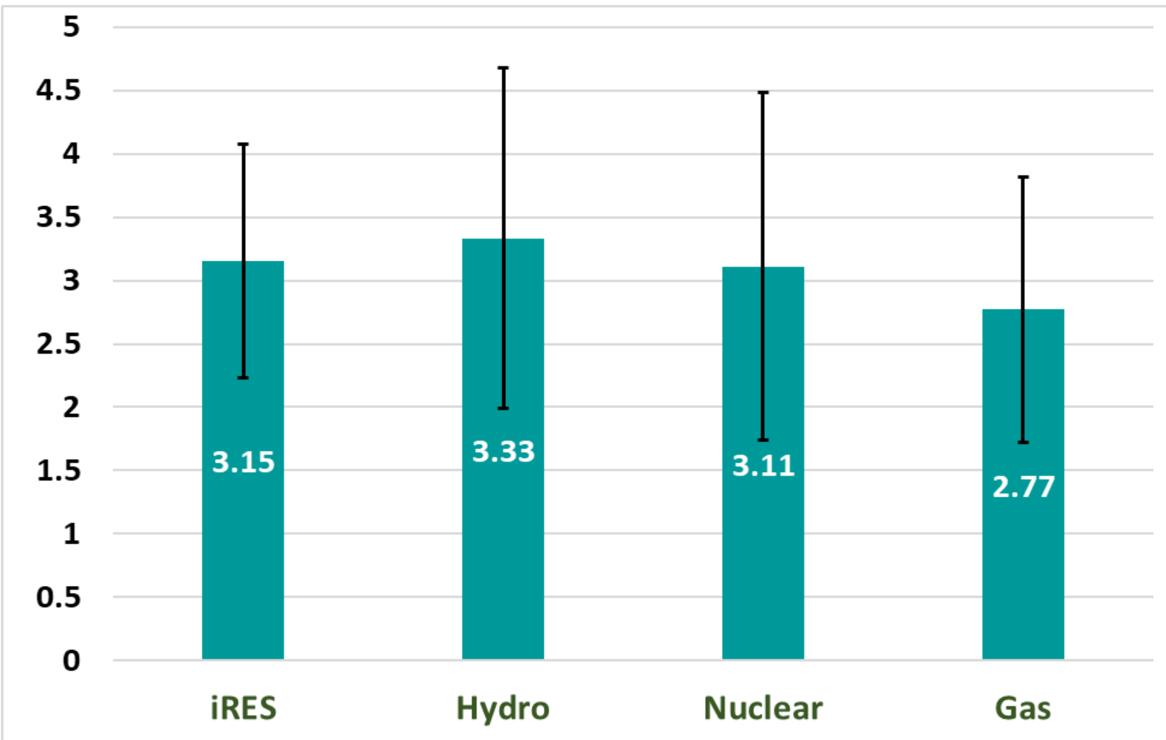


Fig. 4.1.11 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 1.6) Emissions (other than C) (S_i 1.6.2) Ozone depletion potential

- Nuclear (score: 3.11/5) power plants themselves do not emit ozone-depleting substances during operation. However, the lifecycle of nuclear power, including the mining of uranium, the construction of reactors, and the management of nuclear waste, may involve chemicals or processes with a minor ozone depletion potential. Additionally, the use of certain refrigerants and coolants in nuclear facilities may contribute to this potential. The score of 3.11 reflects that nuclear power has a low but notable potential for ozone depletion, primarily due to indirect emissions related to its lifecycle. While these impacts are minimal, they still influence the overall sustainability of nuclear energy with respect to ozone layer protection. Of note, there is some degree of dissensus on this score (longer error bar), possibly translating different judgments on the significant character of these minimal impacts.

- Natural gas (score: 2.77/5) production and use involve processes that may contribute to ozone depletion, particularly through the release of refrigerants and other chemicals used in the extraction, processing, and transportation of natural gas. These substances, while not as significant as those released by other fossil fuels, still have an impact on the ozone layer. The score of 2.77 indicates that natural gas has a higher potential for ozone depletion compared to renewables, nuclear, and hydropower. This is mainly due to the chemical processes involved in its lifecycle, including the use of certain ozone-depleting substances.

These findings highlight the need to consider all environmental impacts, including ozone depletion, when assessing the sustainability of energy sources. While many modern energy technologies have reduced their direct contributions to ozone depletion, the indirect effects associated with their entire lifecycle still need attention to ensure comprehensive environmental protection.

(I 1.6) Emissions (other than C) (S_i 1.6.3) Photochemical oxidant creation potential

Photochemical Oxidant Creation Potential (POCP**)** or photochemical smog is caused by the creation of ozone from volatile organic compounds (VOCs) and nitrogen oxides in the presence of sunlight. Although ozone is critical in the high atmosphere to protect against ultraviolet light, low-level ozone is implicated in impacts as diverse as crop damage and increased incidence of asthma and other respiratory complaints. POCP is usually expressed relative to the oxidant creation potential of ethylene and is expressed using the reference unit, kg C_2H_4 eq/kWh.

The assessment on the sustainability performances for this indicator examines how different energy sources contribute to the formation of photochemical oxidants, primarily ground-level ozone, which is a major component of smog. These oxidants are formed when VOCs and nitrogen oxides (NOx) react in the presence of sunlight, leading to air pollution that can harm human health and ecosystems. The possible scores range from 1 to 5, with higher scores indicating a *lower potential for contributing to photochemical oxidant formation* and therefore better sustainability. The results are presented in Fig. 4.1.12.

The assessment shows that hydropower is the most sustainable option in terms of photochemical oxidant creation potential, with a score of 4.03, followed by nuclear power at 3.50. Both energy sources have minimal direct emissions of the pollutants that contribute to smog. Intermittent renewables have a moderate impact, with a score of 2.95, due to indirect emissions associated with their lifecycle. Natural gas scores the lowest at 2.28, reflecting its significant contribution to NOx emissions and thus to photochemical oxidant formation.

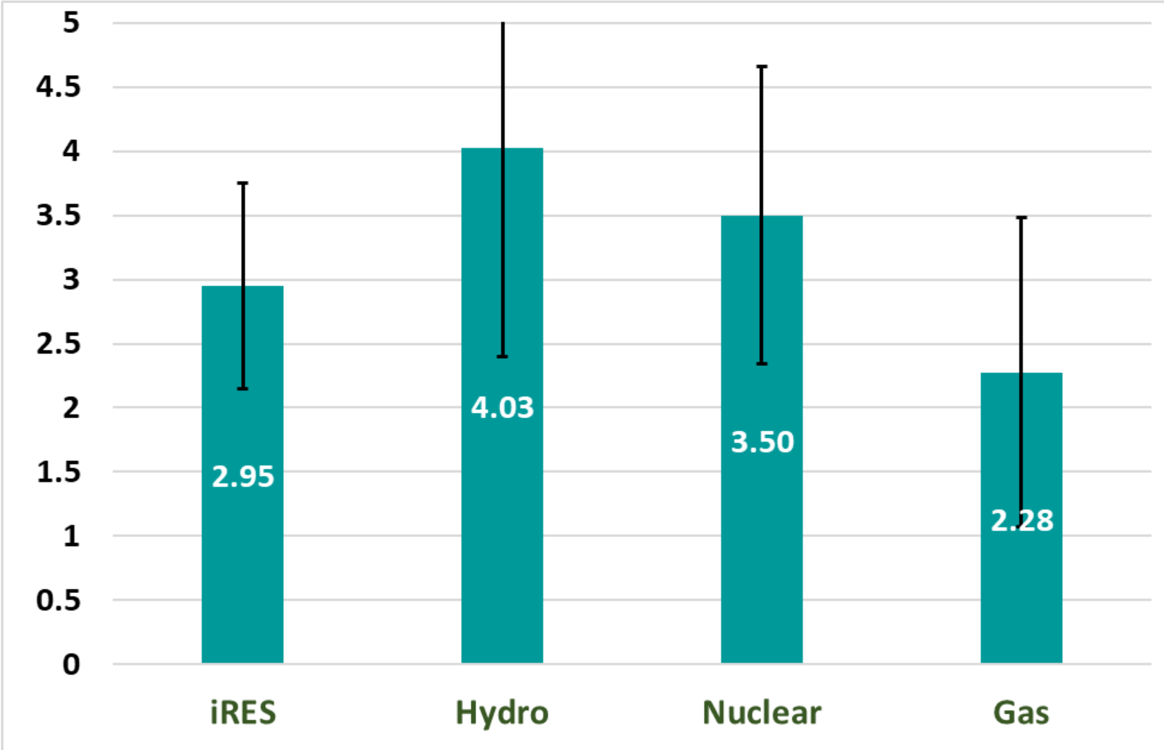


Fig. 4.1.12 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 1.6) Emissions (other than C) (S_i 1.6.3) Photochemical oxidant creation potential

- Hydropower (score: 4.03/5) produces electricity without combustion, so it does not directly emit volatile organic compounds (VOCs) or nitrogen oxides (NOx), which are the precursors to photochemical oxidants. The primary environmental impacts of hydropower relate to land and water use, rather than air emissions. The high score of 4.03 (although comparatively quite dissensual – longer error bar) reflects the very low contribution of hydropower to the creation of photochemical oxidants. Since hydropower plants do not emit the pollutants that lead to smog formation, they are considered highly sustainable in this regard. The slight reduction from a perfect score could account for indirect emissions associated with construction and maintenance activities, but overall, hydropower has minimal impact on air quality in terms of photochemical oxidant creation.

- Nuclear (score: 3.50/5) power plants do not produce VOCs or NOx during operation since they generate electricity through nuclear fission. However, some indirect emissions may occur during the lifecycle of nuclear power, including the mining of uranium, construction of reactors, and transportation of nuclear materials. The score of 3.50 suggests that nuclear power has a low potential for contributing to photochemical oxidant creation, with most of its emissions coming from indirect sources. The clean operation phase makes nuclear power relatively sustainable in terms of this indicator, although lifecycle emissions slightly reduce its score.

- Intermittent renewables (score: 2.95/5) do not involve combustion, so they do not directly emit VOCs or NOx. However, the production, installation, and disposal of iRES technologies may involve some processes that emit these pollutants, particularly during the manufacturing of components like solar panels and wind turbines. The score reflects that while the operational phase of renewable energy sources is clean, the lifecycle emissions associated with manufacturing, transportation, and installation can contribute to the creation of photochemical oxidants. These impacts are relatively moderate, but they are enough to lower the sustainability score compared to hydropower and nuclear energy.

- Natural gas (score: 2.28/5) combustion emits NOx, a key precursor to photochemical oxidants and smog formation. Although natural gas burns more cleanly than coal or oil, it still contributes significantly to the formation of ground-level ozone, especially in areas with high levels of sunlight and VOCs. Additionally, leaks and emissions during extraction and distribution can release VOCs into the atmosphere. The low score (although somewhat dissensual) indicates that natural gas has a substantial potential to contribute to photochemical oxidant creation. While it is cleaner than other fossil fuels in terms of carbon emissions, its contribution to NOx emissions and, consequently, smog formation makes it less sustainable regarding air quality and public health.

These findings emphasize the importance of considering the full lifecycle emissions of energy sources, especially when assessing their impact on air quality. While renewable and nuclear energy sources are generally clean during operation, the indirect emissions associated with their production can still have environmental consequences. Natural gas, despite being a cleaner fossil fuel, remains a significant contributor to smog formation and thus presents challenges for sustainability, particularly in urban areas prone to air pollution.

(I 1.6) Emissions (other than C) (S_i 1.6.4) Cumulative lifecycle emissions of NMVOC and PM2.5

The assessment on the sustainability performances for the indicator "Emissions (other than Carbon), Cumulative Lifecycle Emissions of NMVOC and PM2.5" examines the total emissions of non-methane volatile organic compounds (NMVOC) and particulate matter smaller than 2.5 micrometers (PM2.5) throughout the entire lifecycle of different energy sources. NMVOCs contribute to air pollution and the formation of ground-level ozone, while PM2.5 can cause severe respiratory and cardiovascular health issues. Particulate Matter is a complex mixture of extremely small particles. Particle pollution can be made up of a number of components, including acids (such as nitrates and sulphates), organic chemicals, metals, and soil or dust particles. A multitude of health problems, especially of the respiratory tract, are linked to particle pollution.

The possible scores range from 1 to 5, with higher scores indicating *lower cumulative lifecycle emissions of NMVOC and PM2.5* and thus better sustainability. The results are presented in Fig. 4.1.13.

The assessment shows that nuclear power has the lowest cumulative lifecycle emissions of NMVOCs and PM2.5, earning a score of 3.75, followed closely by hydropower at 3.60. Both energy sources are highly sustainable in terms of minimizing air pollutants across their lifecycles. Intermittent renewables score slightly lower at 3.53, reflecting moderate emissions associated with the lifecycle processes needed to produce and maintain renewable energy infrastructure. Natural gas scores the lowest at 2.95, highlighting its higher emissions of NMVOCs and PM2.5 throughout its lifecycle, making it less sustainable in terms of air quality impacts. The rather marked spread of opinions (long error bars) on this indicator for all technologies suggests that similarly to the NOx and SO_2 emissions, these pollutants are either less well known or more complex in interpretation.

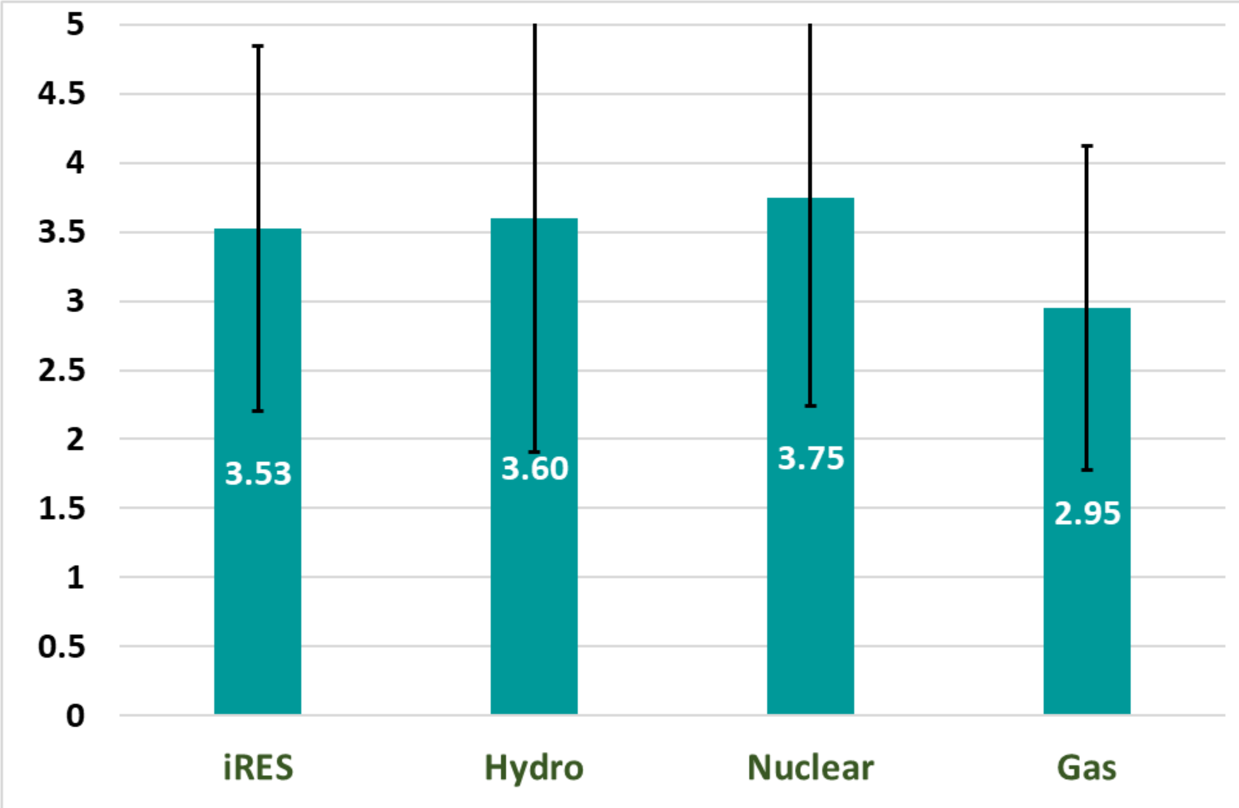


Fig. 4.1.13 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 1.6) Emissions (other than C) (S_i 1.6.4) Cumulative lifecycle emissions of NMVOC and PM2.5

- Nuclear power plants (score: 3.75/5) have low emissions of NMVOCs and PM2.5 during their operation since they do not involve combustion processes. Most emissions occur during the lifecycle phases, including uranium mining, fuel processing, and the construction and decommissioning of nuclear facilities. However, these emissions are generally lower than those associated with fossil fuel-based power generation. The high sustainability score highlights nuclear energy as a clean option in terms of air quality impacts, particularly when compared to fossil fuels. The main emissions are indirect, arising from ancillary activities rather than the power generation process itself.
- Hydropower (score: 3.60/5) also produces very low NMVOC and PM2.5 emissions during operation since it does not rely on combustion. Most emissions come from the construction, maintenance, and eventual decommissioning of dams and power stations. These phases may involve the use of machinery and materials that contribute to NMVOC and PM2.5 emissions, but overall, these are relatively limited. The score of 3.60 indicates that hydropower has low cumulative lifecycle emissions, making it a sustainable energy source in this respect. While there are some emissions associated with the construction and infrastructure maintenance phases, they are minor compared to the ongoing operational benefits of low emissions.
- Intermittent renewables (score: 3.53/5) have very low operational emissions of NMVOCs and PM2.5 since they do not involve combustion. However, the lifecycle of renewable technologies—including the manufacturing, transportation, installation, and decommissioning of solar panels and wind turbines—can result in emissions of NMVOCs and PM2.5. The extraction and processing of materials needed for these technologies also contribute to these emissions. The score of 3.53 reflects the relatively low but still significant lifecycle emissions associated with

renewable energy technologies. These emissions are generally higher than those for hydropower and nuclear power due to the intensive material and manufacturing processes required for renewable energy infrastructure. Nonetheless, the overall impact is moderate, making renewables a fairly sustainable choice in this context.

- Natural gas (score: 2.95/5) combustion produces NMVOCs and PM2.5, though at lower levels than coal or oil. Additionally, emissions occur during the extraction, processing, and distribution of natural gas. These processes can release NMVOCs into the atmosphere, particularly through leaks and flaring. The overall lifecycle emissions of PM2.5 and NMVOCs from natural gas are higher than those from non-combustion-based energy sources. While it is considered a cleaner fossil fuel, its lifecycle emissions still contribute significantly to air pollution, which negatively impacts sustainability in terms of public health and environmental quality.

These results, although overall composed of noticeable variability across raters and technologies, emphasize that while renewable energy and nuclear power offer significant benefits in reducing operational emissions, attention must also be given to their lifecycle impacts. In contrast, natural gas, despite being a cleaner alternative to other fossil fuels, still contributes to air pollution, particularly through NMVOC and PM2.5 emissions, which are important considerations for long-term sustainability and public health.

(I 1.7) Impact on life and ecosystems (under normal operation) (S_i 1.7.1) Human toxicity potential

Human toxicity potential is a measure of the effect of toxic substances on human health considering all exposure routes for all chemicals for an infinite time frame. Important contributing substances include heavy metals as well as particulate matter, SO_x and NO_x emissions, volatile organic compounds (VOC) and chlorinated organic compounds among others. The indicator used to categorize human toxicity potential is measured in 1,4-dichlorobenzene equivalent/kWh.

The assessment of sustainability performances for this indicator examines how different energy sources impact human health through potential toxicity under normal operational conditions. Human toxicity potential considers the release of harmful substances that can affect human health, such as heavy metals, radioactive materials, or chemical pollutants. The possible scores range from 1 to 5, with higher scores indicating *lower potential for human toxicity* and thus better sustainability. The results are presented in Fig. 4.1.14.

The assessment shows that hydropower on average is viewed as having the lowest human toxicity potential, with a score of 3.90, reflecting its relatively reduced impact on human health under normal operation. Nuclear power follows with a score of 3.38, indicating moderate human toxicity potential, mainly due to the management of radioactive materials. Natural gas scores 3.10, suggesting a moderate impact due to potential pollutants and leaks associated with its lifecycle. Intermittent renewables score the lowest at 2.75, reflecting, in the opinion of the respondents, higher human toxicity potential due to the use of toxic materials in manufacturing and insufficient maturity of the management for the disposal phase.

- Hydropower (score: 3.90/5) has a relatively low human toxicity potential under normal operation. The primary environmental concerns with hydropower are related to the construction of dams, which can lead to habitat disruption and localized chemical contamination. However, once operational, hydropower plants typically do not emit significant levels of toxic substances. The minor impacts that do occur are usually localized and related to the construction and maintenance of infrastructure rather than ongoing operations. This makes hydropower one of the more sustainable options in terms of minimizing human toxicity under normal operation. The relatively higher dispersion of respondent opinions (long error bar) suggests that individual raters may be more or less sensitive to these diverse impacts, or have varying levels of awareness or knowledge.

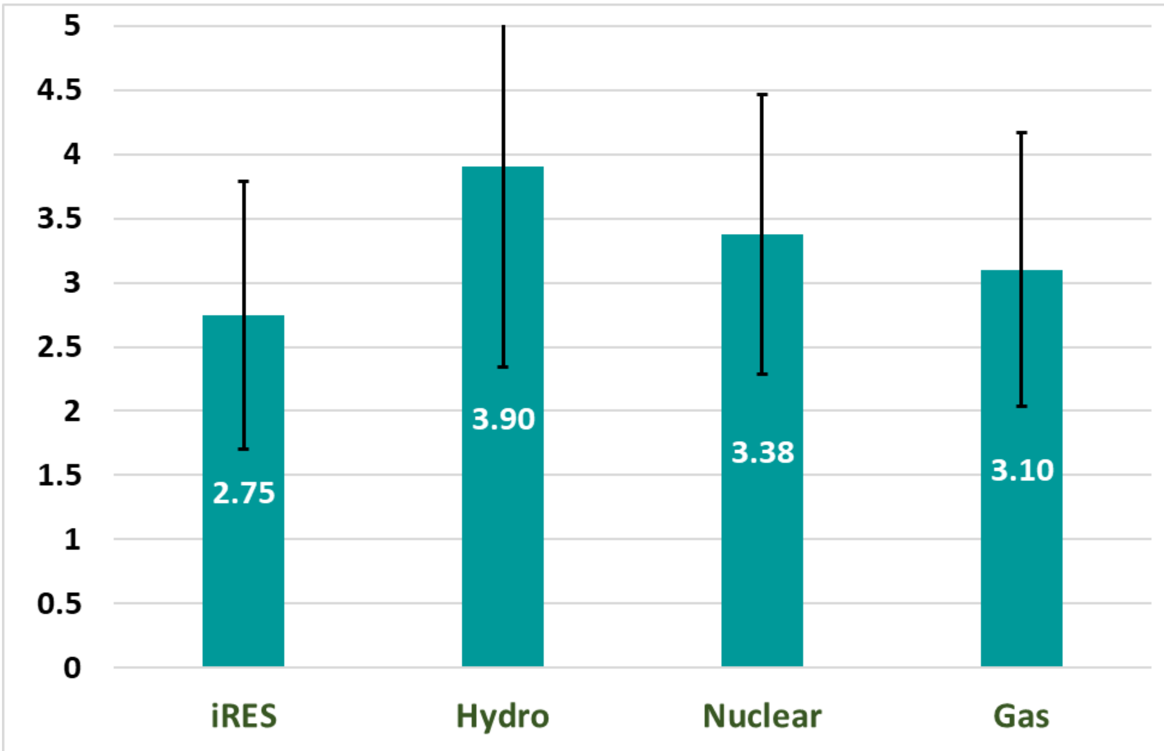


Fig. 4.1.14 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 1.7) Impact on life and ecosystems (under normal operation) (S_i 1.7.1) Human toxicity potential

- Nuclear (score: 3.38/5) power plants do not emit harmful substances under normal operation; however, there are potential risks associated with the handling of radioactive materials, spent fuel, and waste management. The current indicator does not take into consideration the accidents since it refers to the normal operation. Proper containment and management systems are crucial to minimize the risk of radioactive contamination and ensure safety during entire operation process. The score of 3.38 suggests a moderate human toxicity potential. While nuclear power plants are designed to prevent harmful emissions during normal operation, the risks associated with radioactive materials remain considerable. The controlled operational conditions generally limit these risks, but they are significant enough to affect the sustainability score.
- Natural gas (score: 3.10/5) combustion does not produce highly toxic substances under normal operation. However, the extraction, processing, and distribution of natural gas can involve the release of various pollutants and chemicals that may have health impacts. Additionally, methane leaks during extraction and transportation can contribute to health risks. The score of 3.10 reflects a moderate impact on human toxicity potential. While natural gas is cleaner than other fossil fuels, it still involves some level of toxicity due to the chemicals used in extraction and potential leaks. These factors contribute to its lower score compared to hydropower and nuclear power.

- Intermittent renewables (score: 2.75/5) generally have low toxicity impacts during operation. However, the manufacturing, transportation, and disposal of renewable energy components like solar panels and wind turbines can involve toxic materials and chemicals, such as heavy metals and rare earth elements. The low score of 2.75 indicates a higher potential for human toxicity, in the opinion of the respondents, compared to other energy sources. While operational emissions are minimal, the lifecycle of renewable technologies involves the use and potential release of toxic materials, which affects the overall score. This highlights the need to consider not only the operational phase but also the broader lifecycle impacts of renewable technologies.

These results underscore that while intermittent renewables and other energy sources may offer significant environmental and operational benefits, their lifecycle impacts, including human toxicity, must be carefully managed. Hydropower and nuclear power generally present lower risks under normal operation, but all energy sources have unique challenges that need to be addressed to improve overall sustainability.

(I 1.7) Impact on life and ecosystems (under normal operation) (S_i 1.7.2) Human health/mortality impact

The indicator Human Health/Mortality Impact examines the effects of an energy source on human health and mortality, specifically under normal operational conditions. Considering the scope of the assessment the respondents were invited to take into account the entire life cycle of each alternative technology. This indicator assesses how the energy production process affects the health of populations and can lead to increased rates of illness or premature death, including the other stages of technology life for example the upstream part.

The focus is on direct and indirect impacts related to the energy source's operation, including: air pollution (for example the contribution of these pollutants to health issues such as asthma, lung cancer, heart disease, and overall mortality rates), toxicity (assessing the risk of diseases or health conditions resulting from exposure to these toxic elements, including potential long-term health effects), accidents and incidents (assessing the potential for immediate and long-term health consequences from such accidents, including injuries and fatalities), environmental degradation (assessing how environmental changes lead to health issues such as contaminated drinking water, reduced air quality, and increased disease vectors), lifecycle considerations (such as exposure to pollutants during the manufacturing and disposal phases of energy technologies).

The assessment on the sustainability performances for this indicator examines how different energy sources affect human health and mortality rates under normal operational conditions. This indicator considers the direct and indirect health effects associated with the energy production process, including air and water pollution, toxic exposure, and other environmental impacts that can lead to adverse health outcomes. The possible scores range from 1 to 5, with higher scores indicating *lower impacts on human health and mortality*, thus reflecting better sustainability. The results are presented in Fig.4.1.15.

The assessment reveals that hydropower scores the highest at 4.00, reflecting its minimal direct impact on human health and mortality under normal operation. Intermittent renewables score 3.54, indicating a low health impact, although lifecycle considerations slightly reduce their score. Nuclear power scores 2.90, highlighting moderate health risks due to potential radioactive materials and waste management challenges. Natural gas scores the lowest at 2.85, indicating the highest impact on human health and mortality due to pollutants and methane leaks.

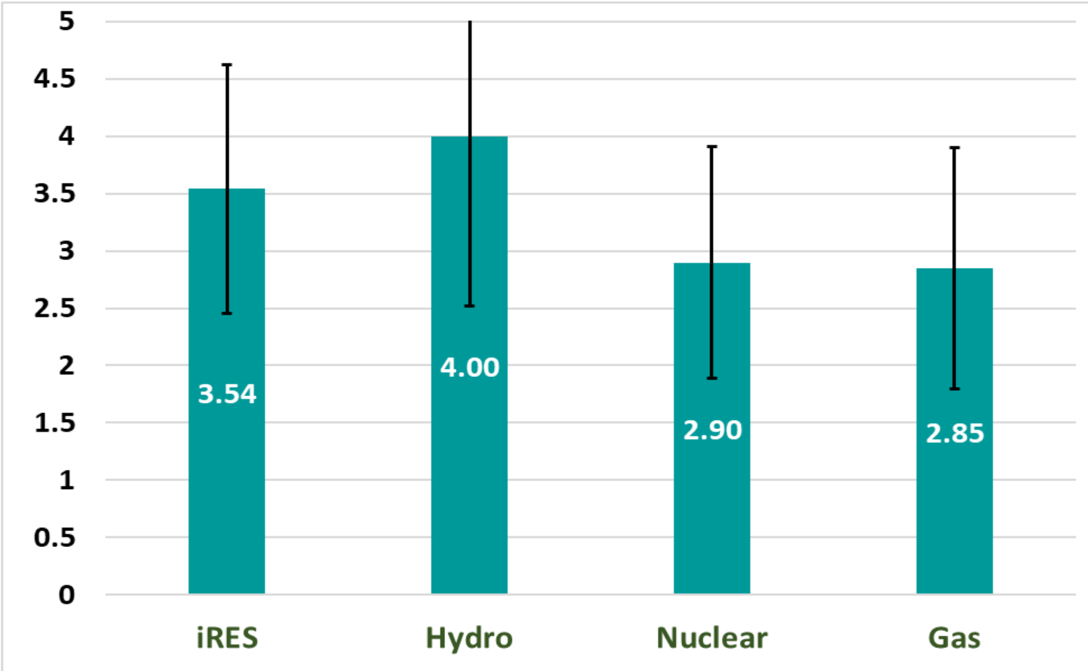


Fig. 4.1.15 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 1.7) Impact on life and ecosystems (under normal operation) (S_i 1.7.2) Human health/mortality impact

- Hydropower (score: 4.00/5) generally has low direct impacts on human health and mortality under normal operation. The primary concerns are associated with the construction and maintenance of dams, which can involve localized disruptions and potential health impacts related to the displacement of communities and changes in local ecosystems. However, once operational, hydropower does not produce emissions or pollutants that significantly affect human health. The high mean score of 4.00 reflects hydropower's relatively low impact on human health and mortality. While there are some indirect effects related to the construction and environmental changes, the operational phase is considered very clean. The concerns in relation with possible catastrophic event like the rupture of a dam are not considered by this indicator since it refers to normal operation conditions. This makes hydropower a sustainable choice with minimal health impacts under normal conditions. Again, however, the relatively high dispersion of opinions within this assessment (long error bar) suggests that different raters are more or less sensitive to these impacts, or perhaps have different levels of knowledge about them.

- Intermittent renewables (score: 3.54/5) have low direct health impacts during operation since they do not involve combustion or emissions. The score of 3.54 suggests that intermittent renewables have a relatively low impact on human health and mortality. The operational phase is clean, but the lifecycle impacts, including potential exposure to toxic materials from manufacturing and disposal, slightly reduce the score. Despite these lifecycle considerations, renewables are still a sustainable option with a generally positive health impact profile.

- Nuclear power (score: 2.90/5) have minimal direct emissions during operation, but there are potential risks related to radioactive materials and waste management. The risks of accidental releases and long-term waste disposal can have significant health implications. The score of 2.90 indicates a quite moderate impact on human health and mortality. These risks are significant enough to reduce the score, despite the low direct emissions during normal operation.

- Natural gas (score: 2.85/5) combustion results in lower direct emissions compared to coal and oil but still contributes to air pollution through the release of NOx and other pollutants The score of 2.85 reflects that natural gas has the lowest score among the considered energy sources, indicating a significant impact on human health and mortality. The health impacts primarily arise from air pollution and methane leaks, which can affect respiratory health and contribute to broader environmental issues.

These results emphasize that while renewable and hydropower options generally present lower health risks, considerations must extend beyond operational phases to include lifecycle impacts. Nuclear power and natural gas, despite being cleaner than other fossil fuels in some respects, still pose significant health risks that need careful management to improve overall sustainability.

(I 1.7) Impact on life and ecosystems (under normal operation) (S_i 1.7.3) Ecotoxicity

Ecotoxicity is an important indicator used to assess the sustainability performance of energy technologies. It refers to the potential for a substance or a process to cause harmful effects on ecosystems, including plants, animals, and microorganisms, when released into the environment. Ecotoxicity assesses the impact of pollutants, toxic chemicals, or hazardous materials that can disrupt the balance of natural ecosystems, leading to long-term ecological damage.

Environmental toxicity can be assessed by analyzing each impact category for freshwater, marine and terrestrial. Terrestrial ecotoxicity potential refers to the impact on non-human living organisms of terrestrial ecosystems resulting from lifecycle emissions of toxic substances to air, water, and soil. Similarly, definitions for freshwater and marine impact are considered to detail the analysis.

The indicator is expressed in terms of Potentially Disappeared Fraction of species on 1 m^2 of earth surface during one year (PDFm^2 a) per unit of electricity produced. The concept of PDF is defined as the proportion of locally existing species that become extinct (or "disappear") due to exposure to an environmental pressure (land use, ecotoxicity, climate change, eutrophication).

The sustainability performance of various energy technologies was assessed using this indicator with scores ranging from 1 (minimum performance) to 5 (maximum performance, or *lower disappearance of species due to exposure to environmental pressure*). The results are presented in Fig. 4.1.16.

The assessment highlights significant differences in the environmental sustainability of the energy technologies considered. Hydropower (3.89 from 5) stands out as the most ecologically favorable option under normal operating conditions, while intermittent renewables (2.55) and natural gas (2.98) face challenges due to their material extraction processes and emissions. Nuclear energy (3.23), with its low operational emissions but high long-term waste management needs, falls in the middle.

- Hydropower (score: 3.89/5) achieved the highest score, indicating the lowest ecotoxicity impact among the technologies assessed. This score reflects low emissions under normal operation (hydropower plants emit negligible pollutants, contributing to their high score in terms of ecotoxicity.), water management (modern practices often include measures to minimize ecological disruption, such as fish ladders and controlled water releases), long operational lifespan (can operate for decades with relatively low maintenance, reducing the need for frequent material inputs that could contribute to ecotoxicity). However, it is important to note that the construction and initial filling of reservoirs can have significant negative impacts on local ecosystems, including the displacement of species and changes in water quality. The high mean score reflects the balance between these impacts and the low ecotoxicity during normal operation.

Again, there is a marked dispersion in opinion (longer error bar) potentially indicating differences in rater sensitivity, awareness or knowledge.

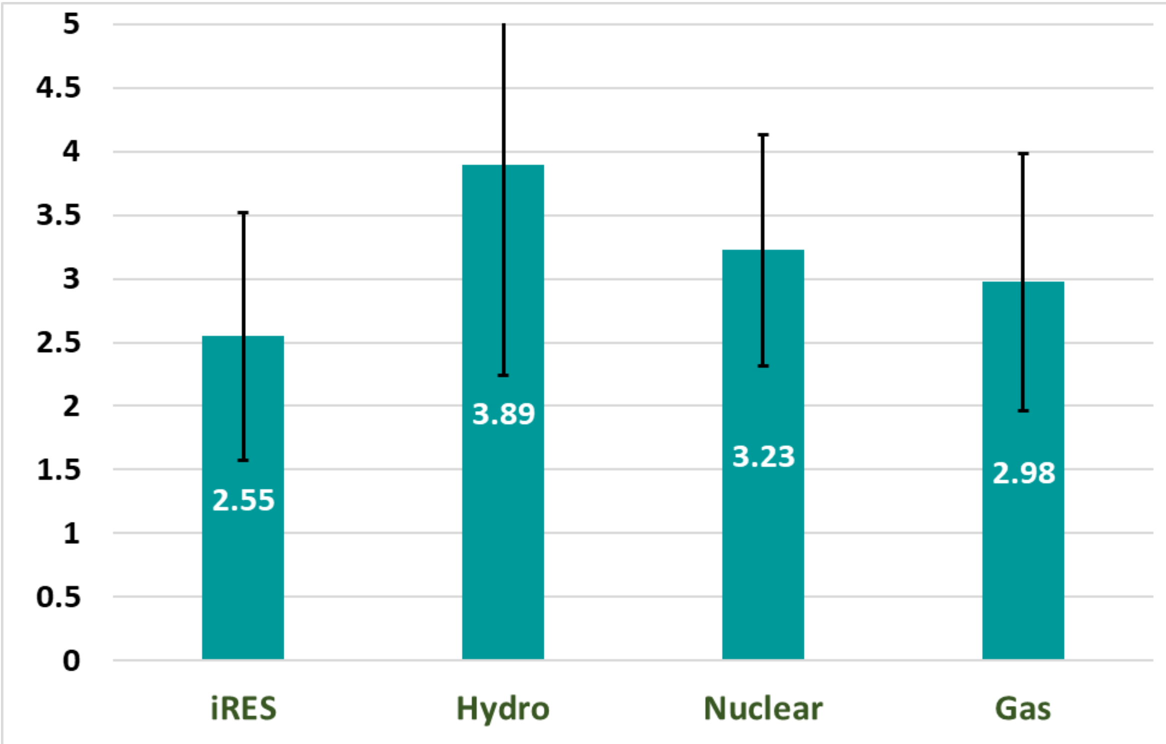


Fig. 4.1.16 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 1.7) Impact on life and ecosystems (under normal operation) (S_i 1.7.3) Ecotoxicity

- Nuclear power (score: 3.23/5) received a score of 3.23, reflecting a moderate impact on life and ecosystems. The score takes into account the following: low operational emissions (low levels of pollutants during normal operation, which contributes to a relatively low ecotoxicity), radioactive waste (requires careful management to prevent environmental contamination; while waste is generally well-contained, the long-term storage and potential for accidents are ongoing concerns), resource extraction (mining and processing of uranium can lead to environmental degradation and ecotoxicity in the surrounding areas). The score reflects a recognition of the low immediate ecological impact of nuclear energy during operation, balanced against the long-term challenges posed by waste management.
- Natural gas (score: 2.98/5) is placed above iRES but below hydropower and nuclear energy. This score reflects several key factors: emissions (its combustion still produces pollutants, including nitrogen oxides and volatile organic compounds, which contribute to air and water pollution, impacting ecosystems), methane leakage (methane can leak during extraction, transportation, and processing), hydraulic fracturing (the process can lead to groundwater contamination and other local ecotoxicity issues, contributing to the technology's moderate score. The score for natural gas reflects the balance between its lower pollutant emissions relative to coal and oil, and the ongoing concerns about methane leakage and fracking-related ecotoxicity.

- Intermittent renewables (score: 2.55/5) received the lowest score indicating a relatively higher impact on life and ecosystems compared to hydropower and nuclear energy. The score reflects several factors such as material extraction (solar panels and wind turbines involves the mining and processing of metals like lithium, cobalt, and rare earth elements, which can lead to significant environmental damage, including habitat destruction and pollution), land use and habitat disruption, end-of-life issues (disposal of solar panels and wind turbine blades, which contain hazardous materials, poses additional challenges and potential ecotoxicity risks). While iRES are essential for reducing greenhouse gas emissions, their lower score in this assessment highlights the need for improvements in material sourcing, recycling, and land use practices to mitigate their impact on ecosystems.

These results emphasize the importance of not only considering the immediate operational impacts of energy technologies but also taking into account the full lifecycle impacts, including resource extraction, waste management, and land use, when assessing their sustainability. As the energy sector continues to evolve, improving the ecotoxicity profile of all technologies will be crucial for achieving a sustainable energy future.

(I 1.7) Impact on life and ecosystems (under normal operation) (S_i 1.7.4) Acidification and eutrophication potential

Acidification potential refers to the compounds that are precursors to acid rain. These include Sulphur dioxide (SO_2), nitrogen oxides (NO_x), nitrogen monoxide (NO), nitrogen dioxide (N_2O), and other various substances. Acidification potential is usually characterized by SO_2-equivalence (g SO_2-eq/kWh).

Eutrophication is the gradual increase in the concentration of phosphorus, nitrogen, and other minerals and plant nutrients in aquatic ecosystems resulting in over-enrichment that can give rise to excessive growth of algae and depletion of oxygen that supports healthy underwater life.

In literature, the indicator for eutrophication potential is expressed in grams phosphate equivalent per unit of electricity generated (gPO_4^{3-}-eq/kWh). Some methodologies calculate freshwater and marine eutrophication potentials separately. As phosphorous is the key limiting nutrient for freshwater eutrophication, its units are g P-eq/kWh, whereas for marine water, nitrogen is most often the key limiting nutrient, so that the units of marine eutrophication are g N-eq/kWh.

The assessment examines how different energy sources affect ecosystems through acidification (which leads to soil and water acidification) and eutrophication (which causes nutrient overloads leading to ecosystem imbalances) under normal operational conditions. This indicator considers the potential environmental damage caused by emissions of nitrogen oxides (NOx), sulfur oxides (SOx), ammonia, and other pollutants associated with each energy source. The possible scores range from 1 to 5, with higher scores indicating *lower impacts on life and ecosystems*, reflecting better sustainability. The results are presented in Fig. 4.1.17.

The assessment reveals that hydropower scores the highest at 3.95, reflecting its minimal contribution to acidification and eutrophication under normal operations. Nuclear power scores 3.54, indicating low impacts, mainly due to the absence of direct emissions during operation, although lifecycle factors slightly reduce its score. Intermittent renewables score 2.95, highlighting the importance of considering lifecycle impacts, as the operational phase is clean but production and disposal have environmental costs. Natural gas scores the lowest at 2.64, indicating higher impacts on life and ecosystems due to emissions contributing to acidification and eutrophication.

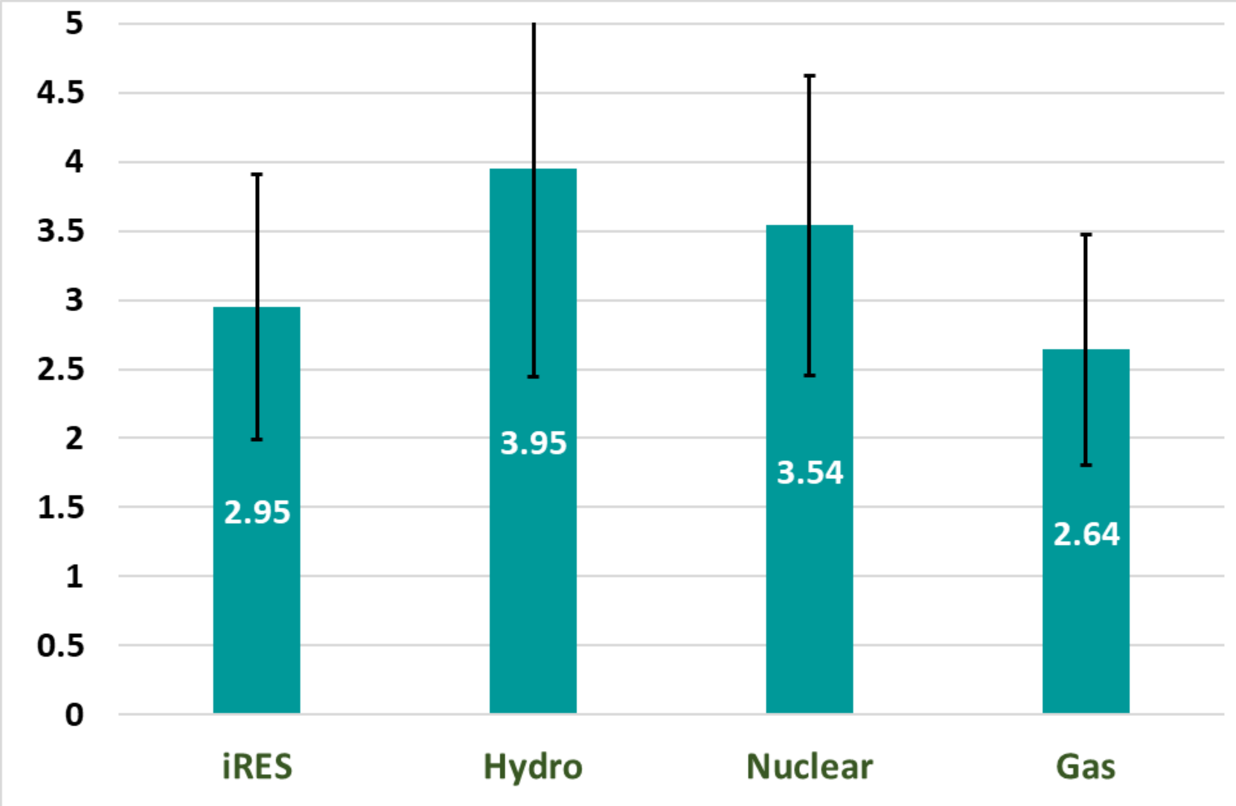


Fig. 4.1.17 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 1.7) Impact on life and ecosystems (under normal operation) (S_i 1.7.4) Acidification and eutrophication potential

- Hydropower (score: 3.95/5) receives a relatively high score, indicating low impacts on life and ecosystems concerning acidification and eutrophication. Of note, however, hydro again shows the largest dispersion of rater opinions, suggesting differential levels of concern, knowledge or awareness. The main concerns with hydropower are related to changes in water flow and quality, which can affect aquatic ecosystems. The high score of 3.95 reflects hydropower's minimal contributions to acidification and eutrophication, making it a more sustainable choice in terms of ecosystem impact. While there are some ecological disruptions related to dam construction and altered water systems, the absence of significant air pollutants contributes to its strong sustainability profile in this area.
- Nuclear power (score: 3.54/5) also scores well, with minimal contributions to acidification and eutrophication. The score of 3.54 indicates that nuclear power has a low impact on acidification and eutrophication, primarily due to the lack of relevant emissions during normal operations. The potential environmental risks associated with the nuclear fuel cycle, such as mining and waste disposal, are relatively minor, contributing to its favorable score.
- Intermittent renewables (score: 2.95/5) score moderately. While these energy sources do not produce emissions during operation, the lifecycle impacts—such as the production and disposal of materials—can contribute to acidification and eutrophication. The score reflects the lifecycle environmental impacts of iRES. Although the operational phase is very clean, the upstream and downstream processes involved in the production and disposal of renewable energy technologies slightly diminish their overall sustainability performance in this area.

- Natural gas (score: 2.64/5) scores the lowest among the considered energy sources, indicating a more significant impact on acidification and eutrophication. Combustion of natural gas releases nitrogen oxides, contributing to acid rain and eutrophication. Additionally, methane leaks during extraction and distribution can exacerbate these environmental issues. The score of 2.64 reflects the higher environmental impact of natural gas concerning acidification and eutrophication. While natural gas is cleaner than coal and oil in terms of overall emissions, it still contributes to air pollution that can harm ecosystems.

These results suggest that while hydropower and nuclear power present lower risks to ecosystems concerning acidification and eutrophication, lifecycle impacts must be carefully managed, especially for renewables. Natural gas, despite being cleaner than other fossil fuels in some respects, still poses significant environmental risks that need to be addressed to improve its overall sustainability.

(I 1.7) Impact on life and ecosystems (under normal operation) (S_i 1.7.5) Freshwater ecotoxicity

Freshwater aquatic ecotoxicity potential, in general terms, refers to the impact on fresh water ecosystems, as a result of emissions of toxic substances to air, water and soil (direct and indirect effects). The toxic effect is causing biodiversity loss and/or species extinction.

The assessment on the sustainability performances for this indicator examines how different energy sources affect freshwater ecosystems through the release of toxic substances. This indicator considers the potential harm to aquatic life from chemicals, heavy metals, and other pollutants associated with each energy source. The possible scores range from 1 to 5, with higher scores indicating *lower impacts on freshwater ecotoxicity*, thus reflecting better sustainability. The results are presented in Fig. 4.1.18.

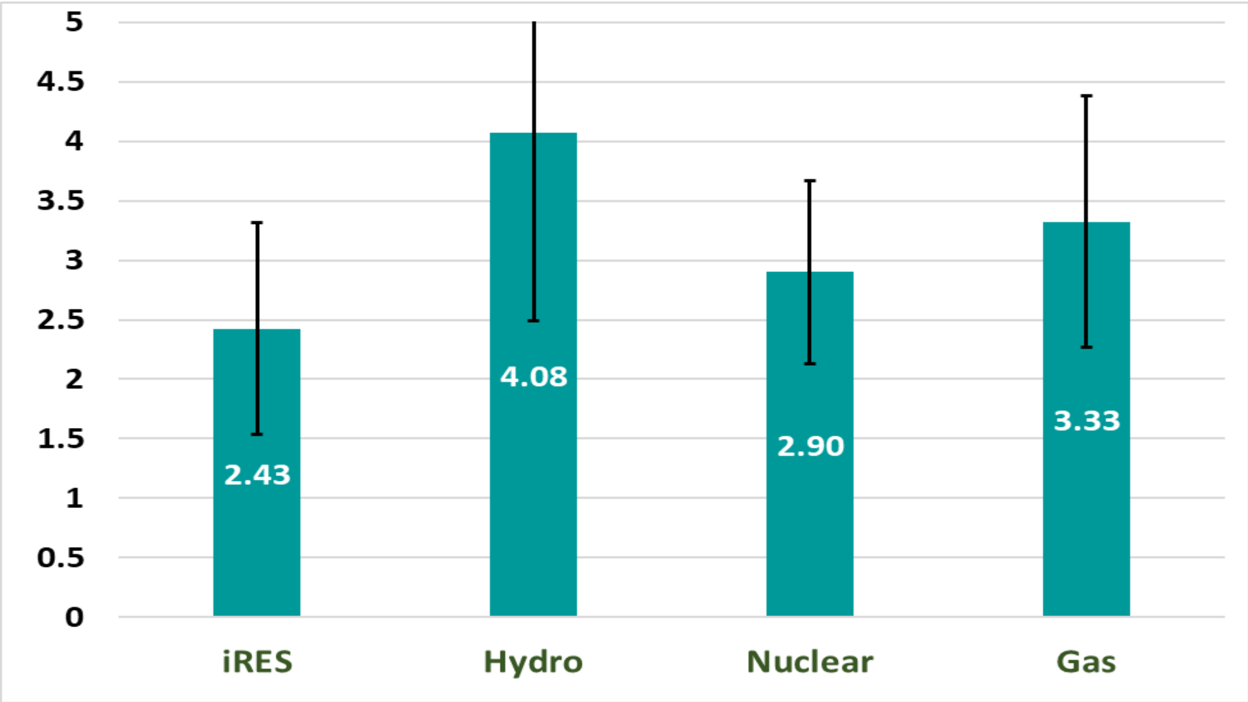


Fig. 4.1.18 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 1.7) Impact on life and ecosystems (under normal operation) (S_i 1.7.5) Freshwater ecotoxicity

The assessment reveals that hydropower scores the highest at 4.08, indicating minimal impact on freshwater ecotoxicity due to the absence of toxic emissions or discharges during normal operation. Natural gas scores 3.33, reflecting a moderate impact that is lower than other fossil fuels but still requires careful management to prevent pollution. Nuclear power scores 2.90, highlighting the risks related to radioactive materials and thermal pollution, which contribute to its moderate impact on freshwater ecosystems. Intermittent renewables score the lowest at 2.43, emphasizing, in the opinion of the respondents, significant lifecycle impacts associated with the manufacturing and disposal of renewable energy technologies, which can negatively affect freshwater ecotoxicity.

- Hydropower (score: 4.08/5) scores the highest, indicating a minimal impact on freshwater ecotoxicity - but note once again the dispersion of opinions (longer error bar). Since hydropower generation primarily involves the mechanical process of converting water flow into electricity, it does not directly introduce harmful chemicals or pollutants into freshwater ecosystems. While the construction of dams and alterations to water flow can have ecological consequences, the lack of toxic emissions or waste during operation makes hydropower one of the most sustainable options in terms of its impact on freshwater ecosystems. This high score underscores the relatively benign nature of hydropower in terms of chemical pollution.
- Natural gas (score: 3.33/5) receives a moderate score, reflecting some potential impact on freshwater ecotoxicity. The extraction, processing, and occasional spills or leaks associated with natural gas production can introduce pollutants into freshwater systems, though these impacts are generally lower than those associated with other fossil fuels. The score of 3.33 indicates that while natural gas has a lower impact on freshwater ecotoxicity compared to other fossil fuels, it is not without risks. Chemical runoff, accidental spills, and leaks can harm aquatic ecosystems, but overall, the impacts are more manageable compared to more polluting energy sources. This score suggests that natural gas, while better than some alternatives, still requires careful management to minimize its ecological footprint.
- Nuclear power’s (score: 2.90/5) score reflects its potential impact on freshwater ecotoxicity, primarily due to the risks associated with the handling of radioactive materials and the cooling water discharge from nuclear plants. While the operational phase of nuclear power does not typically introduce heavy metals or chemicals into freshwater, the potential for contamination from radioactive waste or thermal pollution exists. The score of 2.90 suggests that nuclear power poses quite moderate risks to freshwater ecotoxicity. The key concerns are related to the potential release of radioactive materials into water sources and the impact of heated water discharges on aquatic life. Despite its low carbon footprint, the handling and disposal of nuclear waste and the risks of accidental contamination impact the overall sustainability of nuclear power regarding freshwater ecosystems.
- Intermittent renewables (score: 2.43/5) score the lowest in this assessment. The score reflects the environmental impacts associated with the manufacturing, maintenance, and disposal of renewable energy infrastructure, which can involve toxic substances that, if not properly managed, can leach into freshwater systems. The score of 2.43 indicates that intermittent renewables, despite their clean operational phase, have a significant impact on freshwater ecotoxicity, largely due to lifecycle factors. The production and disposal of photovoltaic cells, wind turbine blades, and batteries involve the use of chemicals and materials that can harm freshwater ecosystems if not properly contained. This score highlights the importance of improving the lifecycle management of renewable energy technologies to enhance their overall sustainability.

These results suggest that while hydropower on average is viewed as presenting the least risk to freshwater ecosystems, even traditionally "clean" energy sources like renewables have environmental challenges that must be addressed. Improving the sustainability of renewable energy technologies, particularly in terms of their lifecycle impacts, will be crucial for reducing their freshwater ecotoxicity footprint. Similarly, managing the risks associated with nuclear power and natural gas will be key to minimizing their ecological impacts.

(I 1.7) Impact on life and ecosystems (under normal operation) (S_i 1.7.6) Marine ecotoxicity

Marine aquatic ecotoxicity potential (MAETP) refers to impacts of toxic substances on marine ecosystems leading to damages on ecosystem quality. The toxic effect is causing biodiversity loss and/or species extinction. In the literature, the indicator is usually expressed as kilograms 1,4-dichlorobenzene equivalents/kWh (kg 1,4-DCB-eq/kWh).

The assessment on the sustainability performances for this indicator examines how different energy sources affect marine ecosystems through the release of toxic substances under normal operational conditions. This indicator considers the potential harm to marine life from chemicals, heavy metals, and other pollutants associated with each energy source. The possible scores range from 1 to 5, with higher scores indicating *lower creation of marine ecotoxicity*, thus reflecting better sustainability. The results are presented in Fig. 4.1.19.

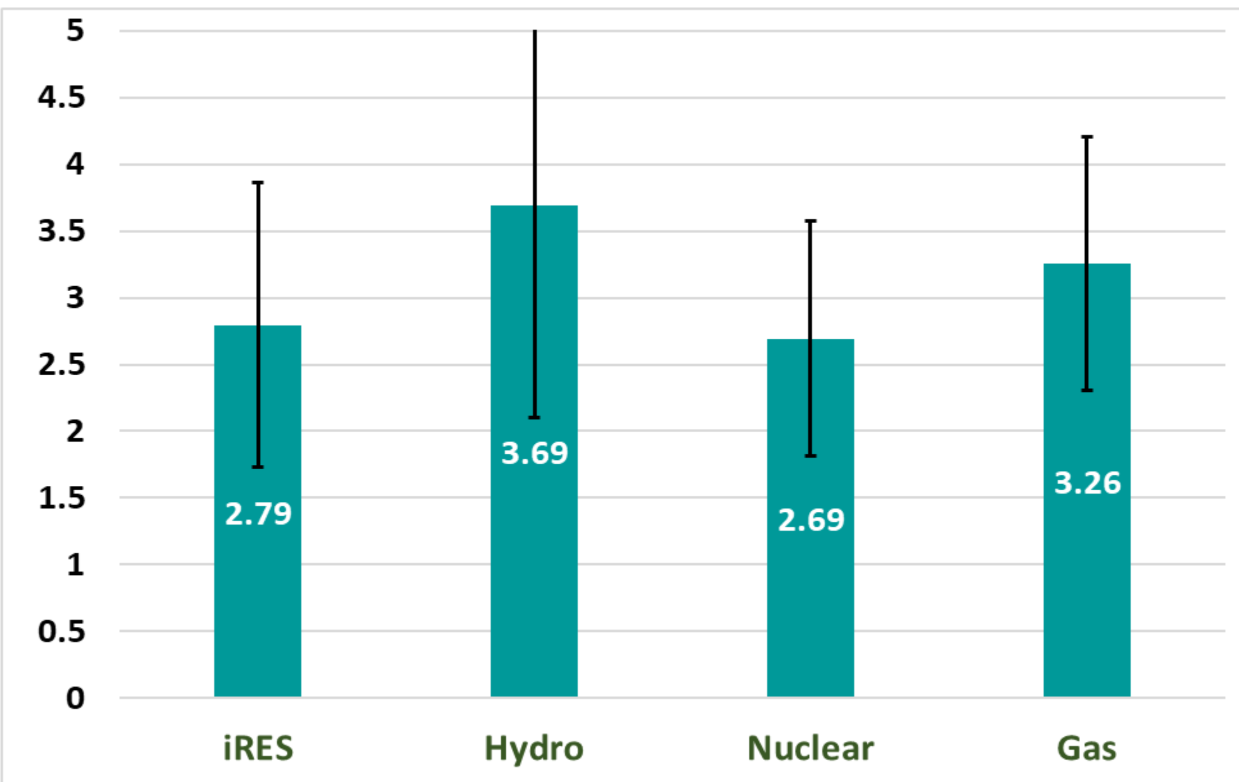


Fig. 4.1.19 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 1.7) Impact on life and ecosystems (under normal operation) (S_i 1.7.6) Marine ecotoxicity

The assessment reveals that hydropower scores the highest at 3.69, reflecting its relatively low impact on marine ecotoxicity due to the absence of significant chemical pollutants, though it can still affect marine environments indirectly. Natural gas scores 3.26, indicating moderate impacts on marine ecosystems, primarily due to the risks associated with offshore drilling and transportation. Intermittent renewables score 2.79, highlighting the lifecycle impacts of manufacturing and installing renewable energy infrastructure, especially in marine environments. Nuclear power scores the lowest at 2.69, reflecting the significant risks of radioactive contamination and thermal pollution affecting marine ecosystems.

- Hydropower (score: 3.69/5) receives the highest score, indicating a relatively low impact on marine ecotoxicity. Since hydropower primarily involves harnessing the energy of flowing water, it does not directly release pollutants into marine environments. However, there can be indirect effects, such as altered water flows and sediment transport, which may affect coastal and marine ecosystems downstream. The score of 3.69 reflects hydropower's minimal contributions to marine ecotoxicity. While hydropower is largely non-polluting in terms of chemical releases, the ecological changes it can cause in connected waterways may impact marine environments, though these impacts are generally less severe compared to other energy sources. This score underscores hydropower's strong sustainability profile in protecting marine ecosystems, but again the dissensual nature of the score (long error bar) must be noted.
- Natural gas (score: 3.26/5) scores moderately high, reflecting its lower impact on marine ecotoxicity compared to other fossil fuels. While the combustion of natural gas produces fewer pollutants than coal or oil, there are still risks associated with offshore drilling, transportation, and potential spills, which can introduce harmful substances into marine environments. The score of 3.26 suggests that natural gas has a moderate impact on marine ecotoxicity, largely due to its cleaner combustion process and lower emissions of harmful substances. However, the risks of marine pollution from accidents and leaks during extraction and transportation, particularly in offshore operations, contribute to its environmental impact. This score indicates that natural gas is relatively sustainable concerning marine ecosystems, though careful management is needed to minimize risks.
- Intermittent renewables (score: 2.79/5) score slightly lower, reflecting their lifecycle impacts on marine ecotoxicity. The manufacturing, installation, and decommissioning of renewable energy infrastructure, such as offshore wind farms, involve materials and processes that can release toxic substances, potentially affecting marine life if not properly managed. The score of 2.79 reflects the challenges associated with the full lifecycle of intermittent renewables in terms of marine ecotoxicity. While the operational phase is clean, the production, maintenance, and disposal of renewable technologies, particularly those installed in marine environments (e.g., offshore wind turbines), can have negative impacts on marine ecosystems. This score highlights the need for improved environmental management throughout the lifecycle of renewable energy technologies to reduce their impact on marine ecotoxicity.
- Nuclear Power (score: 2.69/5) has the lowest score, indicating a relatively higher impact on marine ecotoxicity. This is primarily due to the risks associated with the release of radioactive materials into marine environments, either through accidents or the discharge of cooling water, which can contain trace amounts of radioactive substances and cause thermal pollution. The score of 2.69 indicates that nuclear power poses significant risks to marine ecosystems. The cooling water discharged from nuclear plants can also affect marine life due to temperature changes and possible chemical pollutants. Although nuclear power is a low-carbon energy source, its potential impact on marine ecotoxicity must be carefully managed to mitigate environmental risks.

These results suggest that while hydropower and natural gas are relatively less harmful to marine ecosystems, even energy sources generally considered clean, like renewables, have significant environmental challenges that need to be addressed. For nuclear power, the potential for marine ecotoxicity highlights the importance of stringent safety measures and careful management to protect marine life.

(I 1.7) Impact on life and ecosystems (under normal operation) (S_i 1.7.7) Biodiversity of the used land

Human land use, i.e. changing the natural state of land by human activities, is one of the potential reasons for loss of biodiversity, meaning loss of species. The indicator quantifies the loss of species (flora & fauna) due to land use. It is given in terms of “potentially disappeared fraction” of species on one m^2 of earth surface during one year ($PDFm^2a$) per unit of electricity produced. The concept of PDF is defined as the proportion of locally existing species that become extinct (or "disappear") due to exposure due to an environmental pressure (land use, ecotoxicity, climate change, eutrophication).

The assessment on the sustainability performances for the indicator examines how different energy sources affect biodiversity on the land used for their operations, by considering the direct and indirect impacts on local flora and fauna, including habitat disruption, land use change, and ecosystem fragmentation. The possible scores range from 1 to 5, with higher scores indicating *lower impacts on biodiversity*, thus reflecting better sustainability. The results are presented in Fig. 4.1.20.

The assessment reveals that nuclear power scores the highest at 3.85, indicating a relatively low impact on land biodiversity due to its compact footprint and limited operational land use. Hydropower scores 3.60, reflecting moderate impacts, primarily from initial habitat flooding and alteration during construction, though it has a smaller operational land footprint. Intermittent renewables score 2.98, indicating a moderate impact on land biodiversity due to the significant land required for their infrastructure. Natural gas scores the lowest at 2.90, highlighting the highest impact on land biodiversity due to habitat disruption and the extensive infrastructure needed.

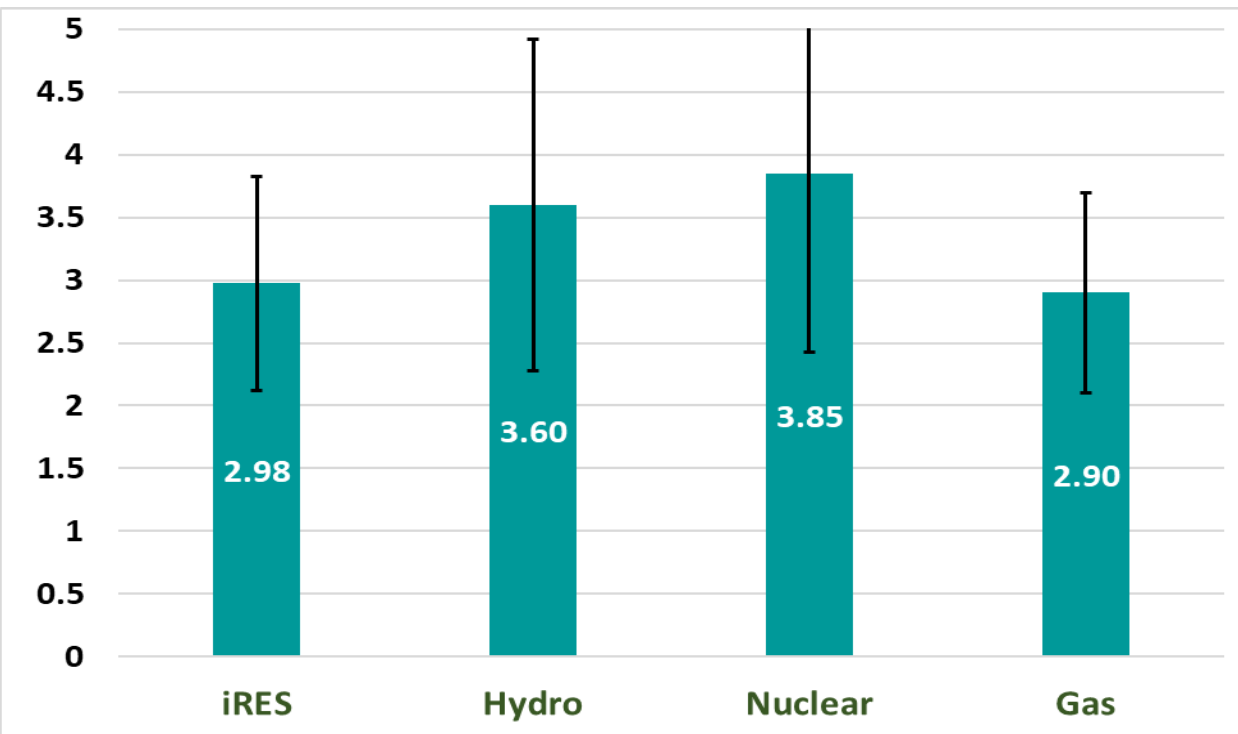


Fig. 4.1.20 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 1.7) Impact on life and ecosystems (under normal operation) (S_i 1.7.7) Biodiversity of the used land

- Nuclear power (score: 3.85/5) scores the highest, indicating relatively low impacts on land biodiversity. Nuclear power plants typically occupy relatively small areas compared to other energy infrastructure, and their direct land use is minimal. However, there can be indirect effects such as habitat disruption during construction and potential impacts from waste storage facilities. The high score of 3.85 reflects that nuclear power, while having some indirect impacts, generally has a lower footprint on land biodiversity. The compact nature of nuclear facilities and the minimal land required for their operation contribute to this positive assessment. Nonetheless, considerations regarding the siting of facilities and management of waste storage are important for maintaining this score. Note that the dispersion of opinion on this indicator is relatively high (longer error bar), which may reflect different sensitivity, awareness or knowledge of these aspects among raters.
- Hydropower (score: 3.60/5) scores well in terms of land biodiversity, as it primarily impacts biodiversity through the construction of dams and reservoirs. The creation of large reservoirs can flood extensive areas, leading to significant changes in local ecosystems and habitat loss. However, once operational, the land directly affected by hydropower plants is relatively small compared to the area impacted by the reservoir. The score reflects a quite moderate impact, acknowledging both the significant land use changes during construction and the relatively lower ongoing land use impact. Again, however, the dissensual character of this mean rating should be noticed, translating the presence of relatively high and low opinions within the assessed value.
- Intermittent renewables (score: 2.98/5) have a moderate impact on land biodiversity. The installation of renewable energy infrastructure can require large areas of land, which may disrupt local habitats and ecosystems. The land used for solar farms and wind turbines can significantly alter the landscape, affecting local flora and fauna. The score of 2.98 suggests that intermittent renewables have a noticeable impact on land biodiversity, primarily due to the land required for their installations. Although the operational phase generally has less impact, the initial land use and the potential for habitat disruption during construction affect the overall score. Improved land management practices and site selection can help mitigate these impacts.
- Natural gas (score: 2.90/5) scores the lowest, reflecting the most significant impact on land biodiversity among the considered energy sources. Natural gas extraction and infrastructure development can lead to habitat fragmentation, soil disturbance, and pollution. The footprint of drilling operations, pipelines, and associated infrastructure can have substantial effects on local ecosystems. The score of 2.90 highlights that natural gas has considerable impacts on land biodiversity, primarily due to the extensive infrastructure required for extraction and transportation. The development and operation of natural gas facilities can disrupt and fragment habitats, affecting local biodiversity. This lower score underscores the need for careful environmental management and mitigation strategies to reduce the impact on land ecosystems.

These results suggest that while nuclear power and hydropower are relatively more sustainable in terms of land biodiversity, intermittent renewables and natural gas present notable challenges. Addressing these impacts involves improving site selection, land management practices, and mitigation measures to enhance the overall sustainability of these energy sources.

(I 1.8) Impact of generated wastes (S_i 1.8.1) Chemical (generated) waste volumes

Usually, the chemical (generated) waste volumes are calculated for plant operation. For nuclear energy, the waste volume includes the waste generated from fuel fabrication and reprocessing. The indicator is presented in g of chemical waste released for 1 kWh of electricity produced by the technology. The respondents were invited to include in their assessment the entire life impact of each of the analyzed technologies.

The assessment on the sustainability performances for this indicator examines how different energy sources affect the environment through the volumes of chemical waste generated during their operation. This indicator considers the types and quantities of chemical wastes produced, which can include hazardous substances, and their potential environmental impacts. The possible scores range from 1 to 5, with higher scores indicating *lower volumes of chemical waste* and thus better sustainability. The results are presented in Fig. 4.1.21.

The assessment reveals that hydropower scores the highest at 4.26, indicating minimal chemical waste generation during operation and reflecting a strong sustainability profile. Nuclear power scores 3.53, showing moderate chemical waste volumes, primarily associated with reactor operations and maintenance. Intermittent renewables score 3.16, reflecting moderate impacts due to lifecycle chemical wastes from production and disposal. Natural gas scores the lowest at 2.45, indicating a perception of the highest volumes of chemical waste, primarily from extraction and processing activities.

- Hydropower (score: 4.26/5) scores the highest, indicating a minimal impact regarding chemical waste volumes. The operational phase of hydropower plants typically does not involve significant chemical processes or waste generation, which contributes to their favorable sustainability profile in this area. This score underscores hydropower's efficiency in terms of chemical waste management.

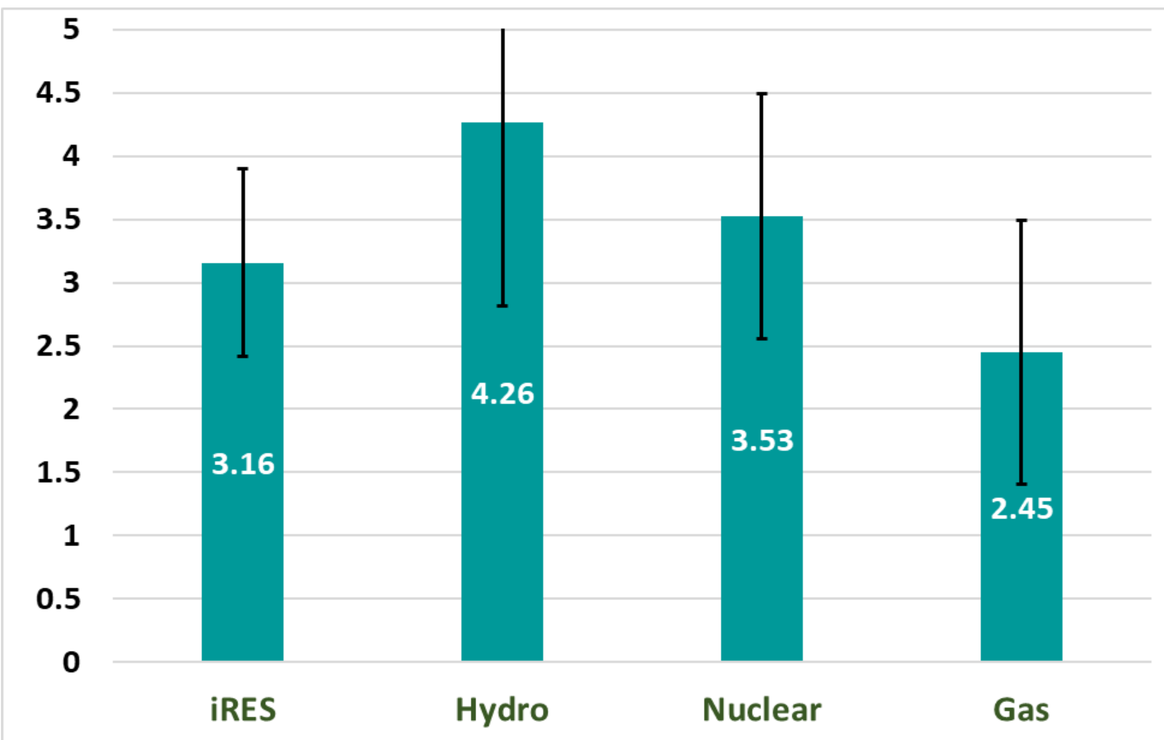


Fig. 4.1.21 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 1.8) Impact of generated wastes (S_i 1.8.1) Chemical (generated) waste volumes

- Nuclear power (score: 3.53/5) has a moderate score, reflecting a higher volume of chemical waste compared to hydropower but still relatively low compared to some other sources. While the primary concern is radioactive waste, chemical waste management is another aspect to be considered. The score of 3.53 indicates that nuclear power has a moderate impact in terms of chemical waste volumes. While nuclear plants are known for generating radioactive waste, the chemical waste associated with their operation, such as cleaning agents and chemicals used in the cooling systems, also needs careful management. The moderate score reflects the complexity of managing these wastes in a sustainable manner.
- Intermittent renewables (score: 3.16/5) score lower due to the chemical waste generated during the production, maintenance, and decommissioning of their infrastructure. This includes waste from manufacturing materials, such as photovoltaic cells and wind turbine blades, which can involve hazardous substances. The score of 3.16 reflects that intermittent renewables have a moderate impact regarding chemical waste. While their operational phase is clean, the lifecycle—including manufacturing, maintenance, and disposal—can produce chemical wastes. This score highlights the importance of improving waste management practices throughout the entire lifecycle of renewable energy technologies.
- Natural gas (score: 2.45/5) scores the lowest, indicating the highest impact on chemical waste volumes among the considered energy sources. Natural gas production and combustion generate various chemical wastes, including those from extraction processes, chemical additives, and potential spills or leaks of pollutants. The score of 2.45 underscores that natural gas has, in the opinion of the respondents, the highest impact on chemical waste generation. The extraction, processing, and use of natural gas is seen as producing significant volumes of chemical wastes, which can pose environmental risks if not properly managed. This lower score reflects the need for improved practices in handling and mitigating the impact of chemical wastes associated with natural gas operations.

These results suggest that while hydropower is the most efficient in minimizing chemical waste, intermittent renewables and nuclear power also have relatively manageable impacts, especially with improved waste management practices. Natural gas, however, presents the greatest challenge in terms of chemical waste volumes, highlighting the need for enhanced waste handling and mitigation strategies to improve overall sustainability.

(I 1.8) Impact of generated wastes (S_i 1.8.2) Radioactive wastes (generated)

The radioactive waste volumes are calculated considering the entire life cycle of each technology, based on available data. The indicator is presented in g of radioactive waste released for 1 kWh of electricity produced by the technology.

The assessment on the sustainability performances for this indicator examines how different energy sources affect the environment through the generation of radioactive waste. This indicator specifically measures the volume and management challenges associated with radioactive materials produced during the energy generation process. The possible scores range from 1 to 5, with higher scores indicating *lower volumes of radioactive waste* and better sustainability. The results are presented in Fig. 4.1.22.

The results reveal that natural gas scores the highest at 4.26, indicating that it generates the least amount of radioactive waste and has a negligible impact in this area. Intermittent renewables and hydropower both score 4.24, reflecting minimal radioactive waste generation and strong sustainability profiles concerning this indicator. In contrast, nuclear power scores the lowest at 2.66, highlighting the significant challenge of managing radioactive waste, which impacts its overall sustainability.

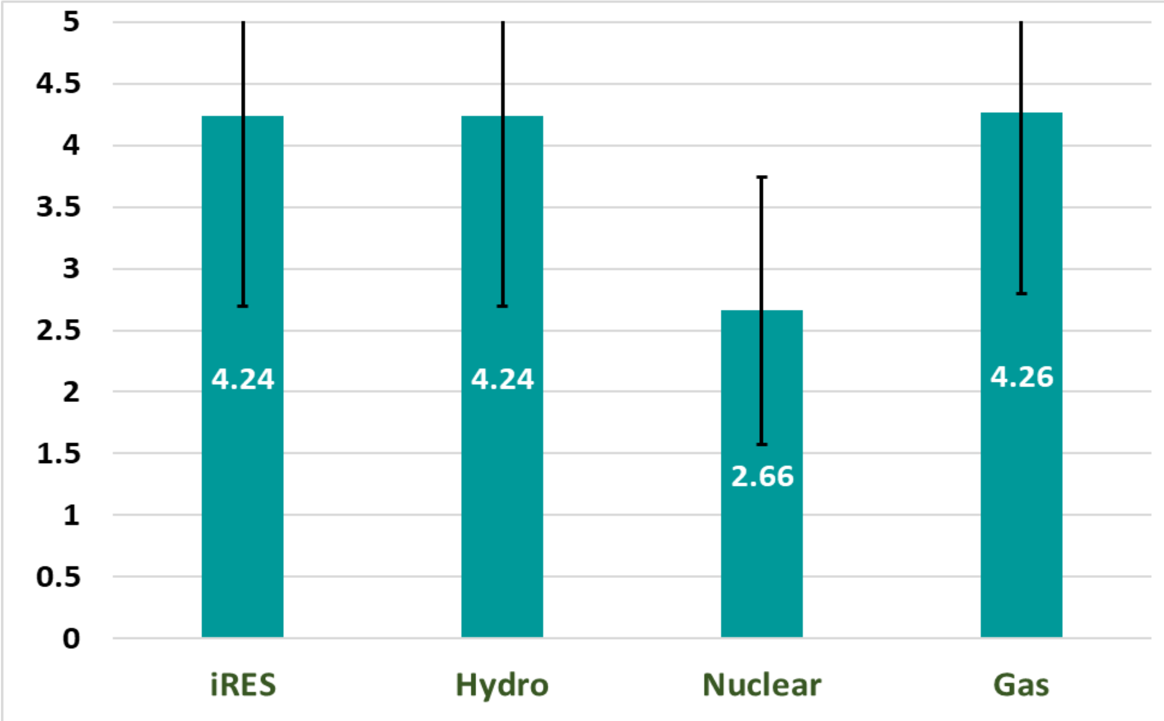


Fig. 4.1.22 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 1.8) Impact of generated wastes (S_i 1.8.2) Radioactive wastes (generated)

- Natural gas (score: 4.26/5) scores the highest, indicating minimal to no generation of radioactive waste. The combustion of natural gas does not produce radioactive materials, and the extraction and processing do not involve radioactive substances. Therefore, natural gas has a negligible impact on radioactive waste generation. The lack of radioactive waste contributes to its strong sustainability profile regarding environmental impact in this area.

- Intermittent renewables (score: 4.24/5) also score very high, indicating minimal radioactive waste generation. The production and operation of renewable energy technologies do not involve radioactive materials, though there may be some minor indirect impacts related to the materials used in manufacturing, which are not typically radioactive.

- Hydropower (score: 4.24/5) scores the same as intermittent renewables, reflecting its minimal generation of radioactive waste. Like other clean energy sources, hydropower does not produce radioactive materials during its operation. The environmental concerns with hydropower are more related to habitat disruption and changes in water systems rather than radioactive waste. Concerns related to sediments accumulation with possible concentration of some natural radioactive elements may produce this perception.

- Nuclear power (score: 2.66/5) scores the lowest, indicating the highest impact on radioactive waste generation. Nuclear power plants produce significant volumes of radioactive waste, including spent nuclear fuel and other radioactive byproducts, which require careful and long-term management. The management and disposal of radioactive waste are major challenges associated with nuclear energy. Despite its low carbon emissions during operation, the generation and management of radioactive waste pose significant sustainability challenges. This score highlights the importance of addressing waste management and safety concerns to improve the overall sustainability of nuclear power.

These results suggest that while renewable sources and natural gas have minimal concerns regarding radioactive waste, nuclear power presents substantial challenges due to the generation and management of radioactive materials. This underscores the need for improved waste management practices and technological advancements in nuclear energy to enhance its sustainability.

(I 1.8) Impact of generated wastes (S_i 1.8.3) Maturity of the approach (experience and effectivity in waste management)

The maturity of the waste management approach has been estimated based the TRL scale, considering the experience and effectivity of this process as applied at present in each energy alternative. Maturity assessment refers to the entire whole life cycle of the energy alternative.

The assessment on the sustainability performances for this indicator examines how well different energy sources manage their waste, focusing on the effectiveness and maturity of waste management practices. This indicator assesses both the experience and the efficacy of waste management strategies used to handle the wastes generated by each energy source. The possible scores range from 1 to 5, with higher scores indicating *more mature and effective waste management practices*. The results are presented in Fig. 4.1.23.

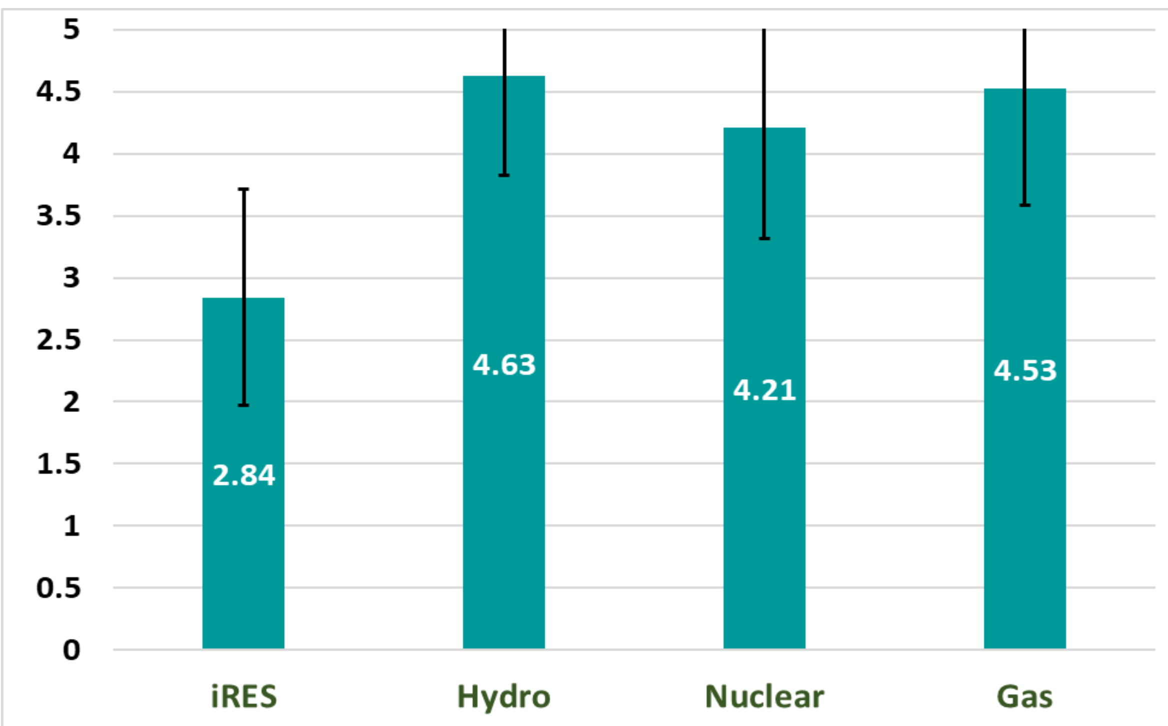


Fig. 4.1.23 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 1.8) Impact of generated wastes (S_i 1.8.3) Maturity of the approach (experience and effectivity in waste management)

The assessment reveals that hydropower scores the highest at 4.63, reflecting a highly mature and effective approach to waste management, largely due to the minimal waste generated. Natural gas follows closely with a score of 4.53, indicating well-established waste management practices despite the environmental challenges associated with its waste streams. Nuclear power scores 4.21, showing robust and effective management of the generated wastes, though the complexity of the waste remains a significant challenge. Intermittent renewables score the lowest at 2.84, highlighting ongoing challenges in developing mature waste management practices for materials associated with renewable energy technologies.

- Hydropower (score: 4.63/5) scores the highest, indicating a very mature and effective approach to waste management. Hydropower plants generally produce minimal waste, and the waste management practices associated with their operation are well-established. The primary concerns with hydropower involve the management of physical debris and sediment, which are relatively straightforward to handle compared to other types of waste. The high score of 4.63 reflects the strong performance of hydropower in terms of waste management maturity. The simplicity and effectiveness of managing the relatively minor waste streams generated contribute to this positive assessment.
- Natural gas (score: 4.53/5) also scores very high, reflecting a well-developed approach to waste management. The natural gas industry has established effective systems for managing wastes such as chemical byproducts and spent materials from extraction and processing. The industry has substantial experience in handling waste from drilling, production, and maintenance activities. The score of 4.53 indicates that natural gas has mature and effective waste management practices. Despite the environmental challenges associated with chemical wastes and potential pollution, the industry's experience and systems in place for managing these wastes contribute to a high score. This suggests that natural gas has made significant progress in improving waste management sustainability.
- Nuclear power (score: 4.21/5) scores well, reflecting a robust approach to managing generated wastes. The nuclear industry has developed sophisticated and highly regulated systems for handling and disposing of wastes including the radioactive materials, such as spent fuel and low-level waste. This involves long-term storage solutions and stringent safety protocols. The score of 4.21 highlights the effectiveness and maturity of waste management practices in the nuclear sector. While the management of waste is complex and involves long-term challenges, the industry's experience and regulatory framework contribute to a strong score. This demonstrates significant efforts to handle waste in a sustainable and safe manner.
- Intermittent renewables (score: 2.84/5) score the lowest, reflecting less mature waste management practices. The production and disposal of renewable energy infrastructure, such as solar panels and wind turbine blades, involve emerging waste management challenges. The industry is still developing effective strategies for managing these materials, which can include hazardous substances. The score of 2.84 indicates that intermittent renewables face significant challenges in waste management maturity. The relatively new and evolving nature of the industry means that effective waste management practices are still being developed and refined. This lower score highlights the need for continued innovation and improvement in managing waste throughout the lifecycle of renewable energy technologies.

These results suggest that while traditional and well-established energy sources like hydropower, natural gas, and nuclear power have developed effective waste management systems, the renewable energy sector is still working towards achieving similar levels of maturity in handling its waste streams. Continued development and innovation in waste management strategies are crucial for improving the sustainability of renewable energy technologies.

(I 1.8) Impact of generated wastes (S_i 1.8.4) Long-term effect of deposited wastes

The long-term effect of the deposited waste has been estimated for entire life cycle of each technology, based on available data in the literature. The indicator is usually linked with the maximum associated risk.

The assessment on this indicator examines the potential long-term environmental effects associated with the disposal of wastes generated by different energy sources. This indicator focuses on how deposited wastes, whether in landfills, storage facilities, or other disposal sites, impact the environment over extended periods. The possible scores range from 1 to 5, with higher scores indicating *fewer long-term environmental impacts* and thus better sustainability. The results are presented in Fig. 4.1.24.

The assessment reveals that hydropower scores the highest at 4.03, indicating relatively low long-term impacts from deposited wastes due to effective management and minimal waste generation. Natural gas scores 3.81, reflecting a moderate long-term impact with well-managed waste practices, but still notable. Intermittent renewables score 3.32, suggesting moderate long-term effects related to the disposal of renewable energy infrastructure, highlighting the need for improved recycling and disposal practices. Nuclear power scores the lowest at 2.74, indicating the highest long-term impact due to the challenges of managing radioactive waste and its potential environmental risks. This latter is also the most consensual opinion represented on this graph (shortest error bar, while the other technologies show noticeable dispersion).

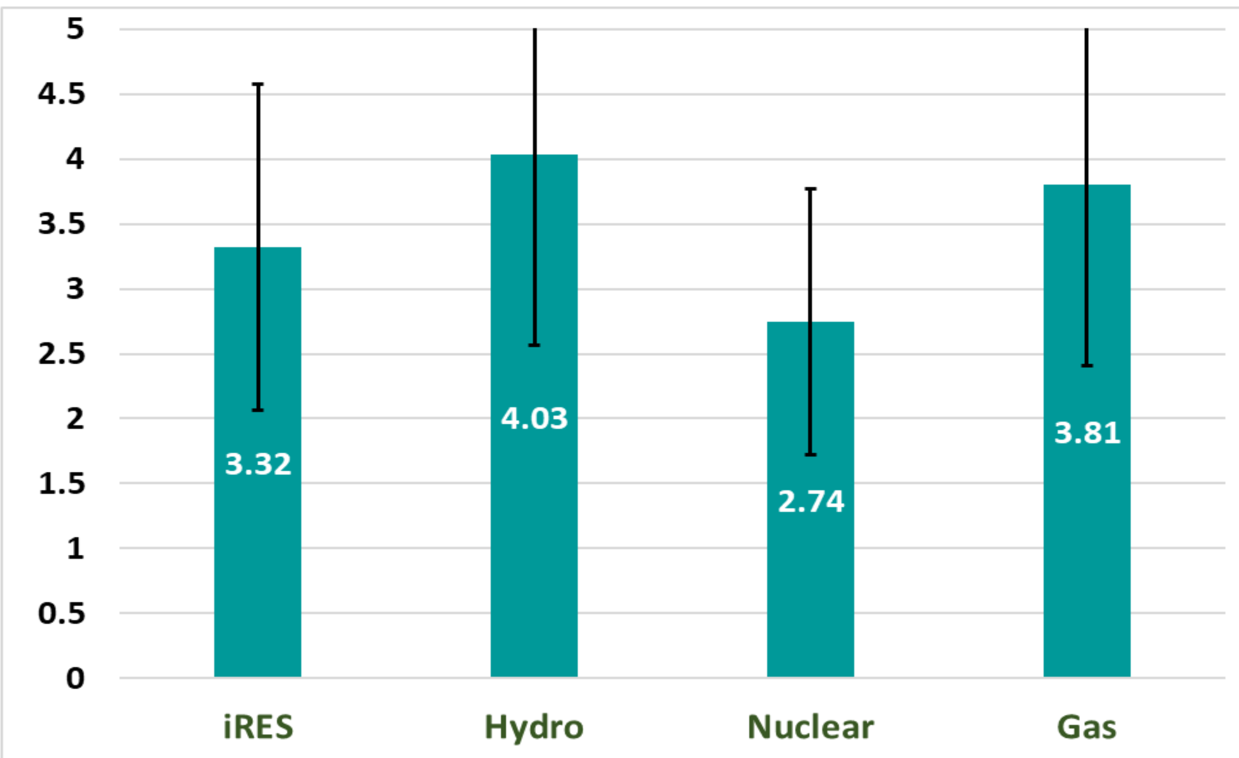


Fig. 4.1.24 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 1.8) Impact of generated wastes (S_i 1.8.4) Long-term effect of deposited wastes

- Hydropower (score: 4.03/5) scores relatively high, reflecting a quite low long-term impact from deposited wastes. While hydropower itself produces minimal waste, the primary long-term concerns arise from the construction of dams and reservoirs, which can lead to sediment accumulation and potential changes in aquatic ecosystems. However, these impacts are generally well-managed and less severe over time compared to some other energy sources. his reflects effective management practices and the relatively low volume of waste generated by hydropower operations.

- Natural gas (score: 3.81/5) scores high, indicating that the long-term effects of deposited wastes are relatively low. Natural gas extraction and processing generate wastes such as drilling muds, chemical byproducts, and spent materials. While these wastes are managed with various technologies and regulations, their long-term impact is typically lower than that of coal or oil, but higher than that of renewable sources. The score of 3.81 reflects that natural gas has a moderate impact on the long-term effects of deposited wastes. The industry has developed effective waste management practices, but challenges remain in ensuring that all deposited wastes do not have adverse long-term environmental effects. The score indicates that while the impact is not negligible, it is relatively well-managed compared to more waste-intensive energy sources.

- Intermittent renewables (score: 3.32/5) score moderately, reflecting a moderate long-term impact from deposited wastes. The main concerns here involve the disposal of components like solar panels and wind turbine blades, which can contain hazardous materials. The industry is still evolving in terms of recycling and disposal practices for these materials. Although the renewable energy sector is making strides in improving the sustainability of waste management, the long-term impacts of disposing of renewable energy infrastructure materials still present challenges. Continued development of recycling and disposal technologies is needed to enhance sustainability.

- Nuclear power (score: 2.74/5) scores the lowest, reflecting the highest long-term impact from deposited wastes. Nuclear power plants generate significant volumes of radioactive waste, which requires long-term storage solutions due to its hazardous nature and prolonged half-lives. The long-term management of radioactive waste involves complex and costly measures to prevent environmental contamination. The challenges associated with radioactive waste management, including secure storage and potential future risks, contribute to this lower score. The long-term sustainability of nuclear power is heavily dependent on effective waste management strategies and ongoing monitoring to mitigate these long-term effects. The relatively consensual nature of the mean score, compared to the other ratings on this indicator, may translate the high visibility of waste management issues among the rater population.

These results suggest that while renewable sources and natural gas generally have more manageable long-term waste impacts, nuclear power presents significant challenges that require ongoing attention and improvement in waste management practices to enhance overall sustainability. These issues are consensually known.

(I 1.9) Impact of accidental situations (S_i 1.9.1) Impact of the accidents (anticipated, design base)

The assessment on the sustainability performances for the indicator "Impact of Accidental Situations, Impact of the Accidents (Anticipated, Design Base)" examines the potential impact of accidents that are anticipated (and considered in the design phase) for within the operational frameworks of different energy sources. This indicator considers how well each energy source handles and mitigates the impact of accidents that are anticipated based on the design and operational procedures.

Anticipated accidents refer to the types of accidents that are expected based on past incidents, historical data, and identified hazards. Design base refers how the design of systems, processes, or infrastructure incorporates measures to mitigate the impact of accidents. It includes assessing the robustness of safety features, emergency response plans, and containment measures designed to handle worst-case scenarios.

Additionally, the preparedness and response measures describe how well the operating organization is equipped to respond to accidents. This includes having effective emergency response plans, training programs, and communication strategies to manage accidents when they occur.

The possible scores range from 1 to 5, with higher scores indicating *better management and lower impact of such accidents*. The results are presented in Fig. 4.1.25.

The assessment reveals that nuclear power scores the highest at 3.43, reflecting relatively strong design and safety measures for handling anticipated accidents. Intermittent renewables and hydropower score similarly at 3.19 and 3.15 respectively, indicating moderate effectiveness in managing the impact of anticipated accidents, with renewable energy sources generally presenting fewer severe risks. Natural gas scores the lowest at 3.06, highlighting challenges in managing the impacts of anticipated accidents, such as explosions and leaks, indicating a need for improved safety protocols and risk management.

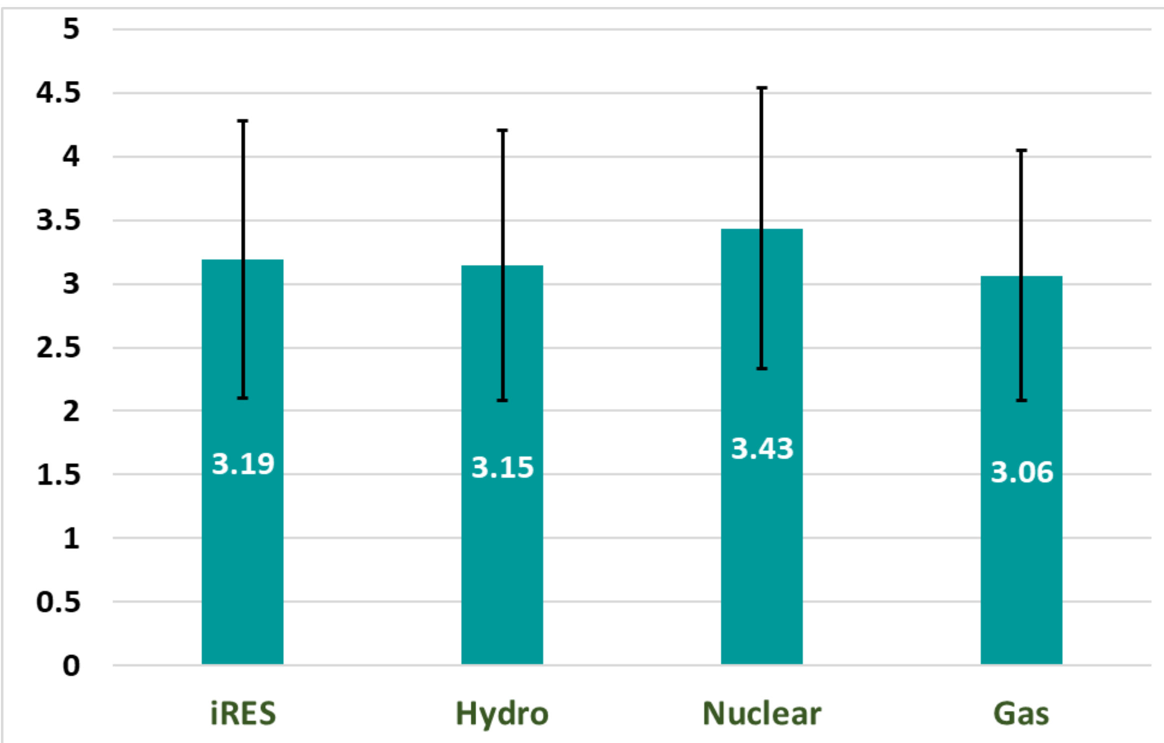


Fig. 4.1.25 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 1.9) Impact of accidental situations (S_i 1.9.1) Impact of the accidents (anticipated, design base)

- Nuclear power (score: 3.43/5) scores the highest among the considered sources, reflecting relatively strong design and safety measures to handle anticipated accidents. The nuclear industry has stringent regulations and safety protocols to manage potential accidents, such as reactor malfunctions or cooling system failures. The design base includes comprehensive emergency preparedness and response plans. The score suggests that nuclear power has relatively effective measures in place to mitigate the impact of anticipated accidents.

- Intermittent renewables (sore: 3.19/5) score moderately in terms of handling the impact of anticipated accidents. The types of accidents in renewable energy facilities are generally less severe compared to nuclear power or fossil fuels. However, issues such as equipment failure, fires, or structural damage can occur and have environmental or safety implications. While these accidents tend to be less hazardous than those in nuclear or fossil fuel energy sources, effective design and safety protocols are still necessary to minimize potential impacts. This score indicates that while renewables have fewer severe risks, managing anticipated accidents remains an important aspect of their sustainability.
- Hydropower (sore: 3.15/5) scores moderately, reflecting a similar level of preparedness for handling anticipated accidents. Potential accidents in hydropower facilities include dam failures or reservoir breaches, which can have significant local environmental and safety impacts. The industry designs and implements safety measures to address such risks, but the potential consequences can be severe. The design and operational safety measures are effective, but the potential severity of accidents like dam failures affects the overall score. The moderate score reflects a balanced approach to risk management and safety in hydropower operations.
- Natural gas (score: 3.06/5) scores the lowest, indicating relatively less effective management of the impacts of anticipated accidents. Potential accidents include explosions, leaks, or fires related to gas extraction, processing, and transportation. The industry has safety measures in place, but the risks and impacts associated with such accidents can be significant. The score of 3.06 reflects that natural gas has somewhat fewer effective measures for handling anticipated accidents compared to other sources. While there are safety protocols and design features to manage risks, the potential for serious incidents like explosions or hazardous leaks impacts the score. This indicates a need for improved safety measures and risk management strategies in the natural gas sector.

These results suggest that while nuclear power has robust safety measures, the other energy sources also demonstrate effective accident management to varying degrees. The varying scores emphasize the importance of continuous improvement in safety designs and emergency preparedness across all energy sectors to enhance overall sustainability.

(I 1.9) Impact of accidental situations (S_i 1.9.2) Impact of severe accidents (considering mitigation/prevention…)

In the nuclear field, severe accidents are those events with extremely low probability of occurrence but causing significant damage of the reactor core, with more or less complete core meltdown and finally possible serious consequences in case of release of radioactive products into the environment

A severe accident in the context of renewable technology is an event that causes significant adverse impact on human health, the environment or the energy system itself. Severe accidents can occur in various types of renewable energy technologies: solar, wind, hydroelectric, geothermal, biomass systems. These accidents can be triggered by a variety of factors, including equipment malfunction, extreme weather events, design flaws, human errors, or unexpected interactions between components.

Some examples of SA in renewable energy systems are dam failures, biomass fires, wind turbine collapses, solar panel explosions. The likelihood and consequences of such accidents are generally much lower compared to nuclear power.

The possible scores range from 1 to 5, with higher scores indicating *better management and lower impact of severe accidents*. The results are presented in Fig. 4.1.26.

The assessment reveals that intermittent renewables score the highest at 3.35, indicating a relatively low impact from severe accidents due to the less hazardous nature of these energy sources and effective mitigation measures. Hydropower follows with a score of 3.11, reflecting a moderate risk where the consequences of severe accidents, particularly dam failures, can be significant. Natural gas scores 2.94, highlighting the risks associated with severe accidents such as explosions and toxic leaks, despite existing safety measures. Nuclear power scores the lowest at 2.81, emphasizing the potentially catastrophic impact of severe nuclear accidents, even with advanced prevention and mitigation efforts.

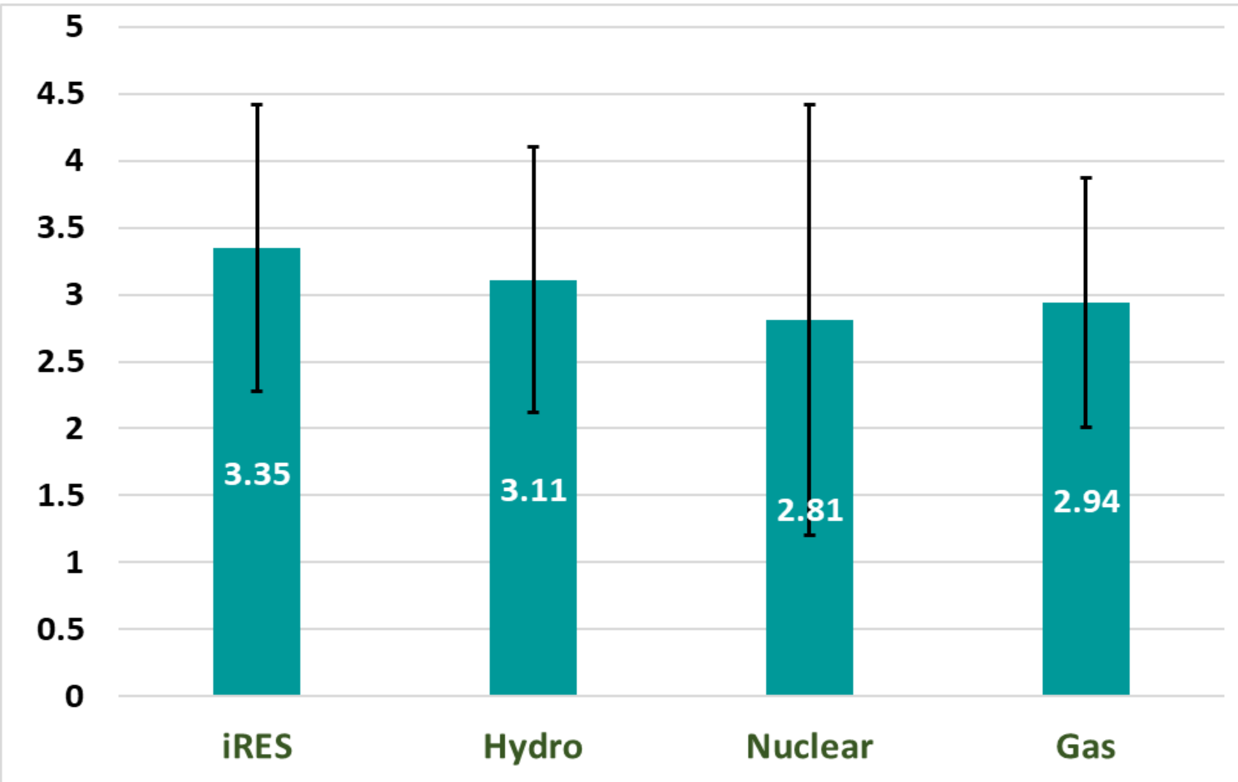


Fig. 4.1.26 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 1.9) Impact of accidental situations (S_i 1.9.2) Impact of severe accidents (considering mitigation/prevention…)

- Intermittent renewables (score: 3.35) obtained the highest generally score. This is because these energy sources have lower inherent risks of severe accidents compared to more conventional energy sources. The primary risks are related to operational failures or extreme weather events affecting the infrastructure, but these risks are relatively minor compared to catastrophic failures. The score of 3.35 indicates a moderate level of impact from severe accidents, with fairly effective mitigation and prevention strategies in place. The lower risk associated with intermittent renewables contributes to this score, but it also reflects that while the inherent risk is lower, there are still operational challenges and occasional failures that need to be managed. Improvements in technology and design can further enhance their safety performance.

- Hydro (score: 3.11) has a somewhat higher risk profile due to potential failures such as dam breaches or flooding. The design and construction of hydroelectric dams require rigorous safety measures, but the consequences of a dam failure can be severe, including significant environmental and human impacts. A score of 3.11 suggests that hydroelectric systems have moderate effectiveness in managing severe accident risks. While there are robust mitigation measures and preventive designs in place, the potential impact of a severe accident remains notable. Advances in dam safety technology and stricter regulatory frameworks have improved safety, but inherent risks persist, affecting the overall score.
- Natural gas (score: 2.94) facilities, including power plants and extraction sites, have risks related to explosions, leaks, and fires. The impact of severe accidents can be significant, though generally less so than nuclear energy. Safety measures and prevention strategies are essential but can vary in effectiveness. With a score of 2.94, natural gas falls in the middle range. This score reflects moderate effectiveness in managing the risks of severe accidents. The potential for accidents like explosions or fires poses a risk, and while there are safety protocols and technologies to mitigate these risks, the effectiveness is not as high as in some renewable energy sources. Enhanced safety measures and technological advancements could improve this score.
- Nuclear (score: 2.81) energy carries the highest risk among the options listed due to the potential for catastrophic accidents, such as reactor meltdowns. The impact of severe accidents can be profound, affecting large areas and populations. However, nuclear facilities are designed with extensive safety and mitigation measures. A score of 2.81 indicates that while nuclear energy has very stringent safety protocols and advanced mitigation measures, the inherent risk associated with severe accidents is perceived as high. The effectiveness of these measures in preventing and managing severe accidents is significant but does not fully mitigate the potential for severe impacts. The lower score reflects the high-stakes nature of nuclear power and the challenges in achieving perfect safety. The strikingly high dissensus of opinion on this indicator (long error bar) suggests that raters bring widely different views on both the severity of nuclear accident impacts, and the potential to mitigate or prevent them.

These results suggest that whereas intermittent renewables and hydropower generally present lower risks in terms of severe accidents, natural gas and nuclear power carry higher risks that require robust safety systems and ongoing improvements in accident prevention and mitigation strategies to enhance overall sustainability. This issue is particularly contentious in this sample regarding nuclear technology.

(I 1.10) Mitigation of accidents (S_i 1.10.1) Inherent safety

Inherent safety is an approach that aims to achieve the safety by elimination or exclusion of the potential hazards through the fundamental conceptual design choices made for the plant. The term is usually generated by nuclear sector.

Inherent safety feature (ISF) represents fundamental property of a design concept that results from the basic choices in the materials used or in other aspects of the design which assures that a particular potential hazard cannot become a safety concern in any way. ISF provide a higher level of safety by relying on natural physical phenomena and properties to control and mitigate potential accidents or failures. ISF are intended to reduce the likelihood of accidents and mitigate their potential consequences.

The assessment on the sustainability performances for this indicator examines the inherent safety features of different energy sources, focusing on the ability of these systems to prevent accidents or minimize their impact by design. Inherent safety refers to the natural properties or built-in features of the energy technology that make it less likely for accidents to occur, and that limit the severity of accidents if they do happen. The possible scores range from 1 to 5, with higher scores indicating *better inherent safety and lower risk of accidents*. The results are presented in Fig. 4.1.27.

The assessment reveals that intermittent renewables score the highest at 4.03, reflecting their strong inherent safety features, which naturally minimize the risk of accidents. Nuclear power follows with a score of 3.86, indicating that despite the potential severity of nuclear accidents, the inherent safety designs are effective at preventing such events. Hydropower scores 3.69, showing good inherent safety, though the potential for dam-related accidents requires ongoing attention. Natural gas scores the lowest at 3.41, reflecting the higher risks associated with its flammable and pressurized nature, despite safety measures in place.

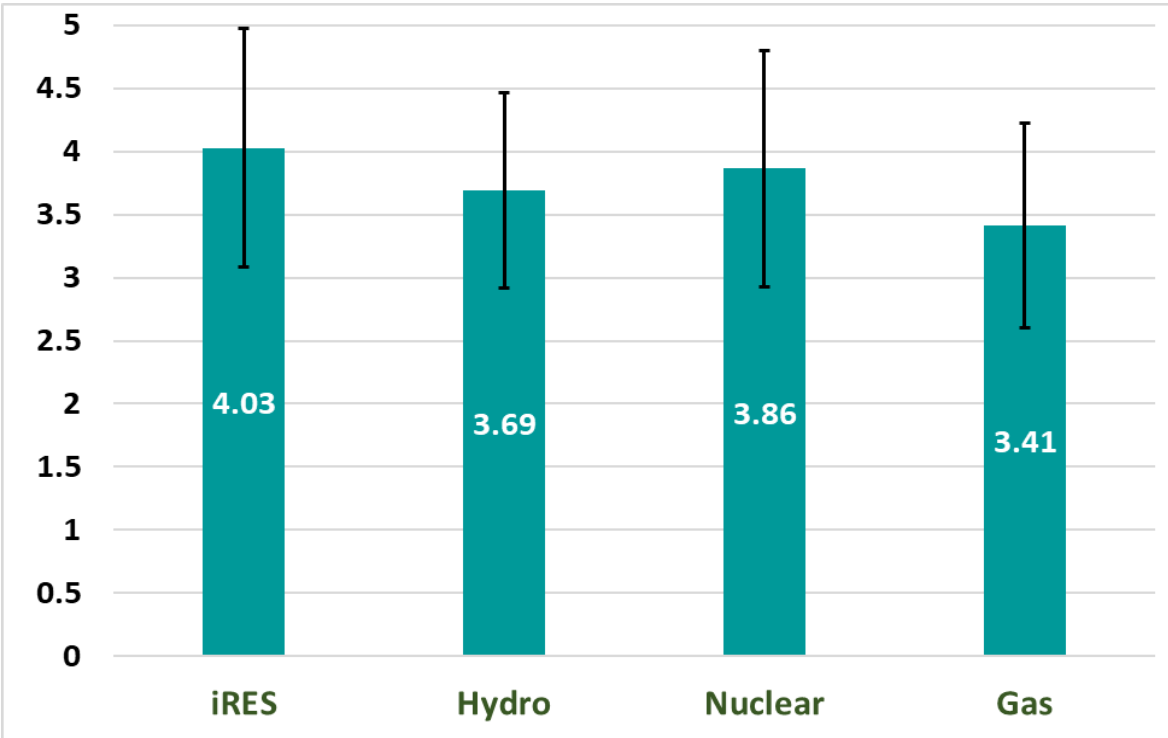


Fig. 4.1.27 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 1.10) Mitigation of accidents (S_i 1.10.1) Inherent safety

- Intermittent renewables (score: 4.03/5) score the highest in inherent safety. These energy sources inherently have fewer hazardous materials and processes involved in their operation, which naturally reduces the risk of relevant accidents. For example, the absence of combustible fuels or high-pressure systems in solar panels and wind turbines contributes to their high inherent safety. This high score indicates that by their very nature, renewables are less prone to serious accidents, supporting their role as sustainable energy sources with minimal risk.
- Nuclear power (score: 3.86/5) scores relatively high in terms of inherent safety, reflecting the advanced safety features integrated into modern nuclear reactors. These include passive safety systems that automatically shut down the reactor in the event of a malfunction, and robust containment structures designed to prevent the release of radioactive materials. While the potential consequences of a nuclear accident are severe, the inherent safety designs are aimed at minimizing the likelihood of such events. The high level of built-in safety measures contributes to

this relatively high score, underscoring the importance of rigorous safety design in mitigating risks associated with nuclear energy.

- Hydropower (score: 3.69/5) scores moderately high in terms of inherent safety, reflecting the generally stable and controllable nature of water-based energy generation. The inherent safety of hydropower comes from the predictability of water flows and the structural integrity of dams and reservoirs. However, the risk of severe accidents, such as dam failures, which can have catastrophic consequences, somewhat lowers the score. While hydropower is generally safe under normal conditions, the need for ongoing monitoring and maintenance of dams is critical to prevent severe accidents. This score suggests that while hydropower has good inherent safety, it still requires careful management to ensure sustainability.
- Natural gas (score: 3.41/5) scores the lowest among the considered energy sources, reflecting a lower level of inherent safety compared to renewables, nuclear, and hydropower. The combustion process, high-pressure systems, and the flammable nature of natural gas increase the risk of accidents. While safety systems are in place, the inherent risks associated with the extraction, transportation, and use of natural gas contribute to a lower score. This highlights the importance of continuous safety improvements and strict regulatory oversight in the natural gas industry to mitigate accident risks and enhance overall sustainability.

These results suggest that while all energy sources have incorporated safety measures, those with fewer inherent risks—such as renewables—tend to have higher inherent safety scores. The inherent safety of nuclear and hydropower is strong (and rather consensually viewed), but the potential for severe consequences necessitates continued vigilance. Natural gas, with its inherent risks, requires the most rigorous safety management to ensure sustainable operations.

(I 1.10) Mitigation of accidents (S_i 1.10.2) Passive systems

Passive systems represent either systems which are composed entirely of passive components and structures or systems which use active components in a very limited way to initiate subsequent passive operation. Passive systems are safety mechanisms that do not require active control or human intervention to function. They rely on natural forces such as gravity, natural convection, or the physical properties of materials to mitigate or prevent accidents. An important motivation for the use of passive safety systems is the potential for enhanced safety through increased safety system reliability and for reducing the likelihood and consequences of accidents.

The term is generated by nuclear industry, but may be extended to any technology in relation with the preventing/mitigation of accidents. For example, for solar cells, passive cooling systems are used for maintaining optimal operating temperatures for solar panels. Wind turbine systems are complex and remotely installed structures which are also subject to many possible faults in the existed components. Early fault detection, isolation and successful controller reconfiguration can considerably increase the performance in faulty conditions and prevent failures in the system. Fault identification determines the type of fault and its severity. In passive fault-tolerant control, a fixed controller is designed that tolerates changes of the plant dynamics.
The assessment for this indicator examines the effectiveness of passive safety systems in various energy sources. The possible scores range from 1 to 5, with higher scores indicating *more effective or reliable passive safety systems*. The results are presented in Fig. 4.1.28.

The assessment reveals that nuclear power scores the highest at 4.08, reflecting the advanced and effective passive safety systems that are crucial for mitigating severe accidents. Intermittent renewables follow closely with a score of 3.97, indicating strong passive safety features, though their inherently lower risks mean less reliance on complex systems. Hydropower scores 3.65, showing effective passive systems, though the nature of water management requires continued vigilance. Natural gas scores the lowest at 3.04, indicating that while some passive systems are in place, they are less comprehensive and effective compared to other energy sources.

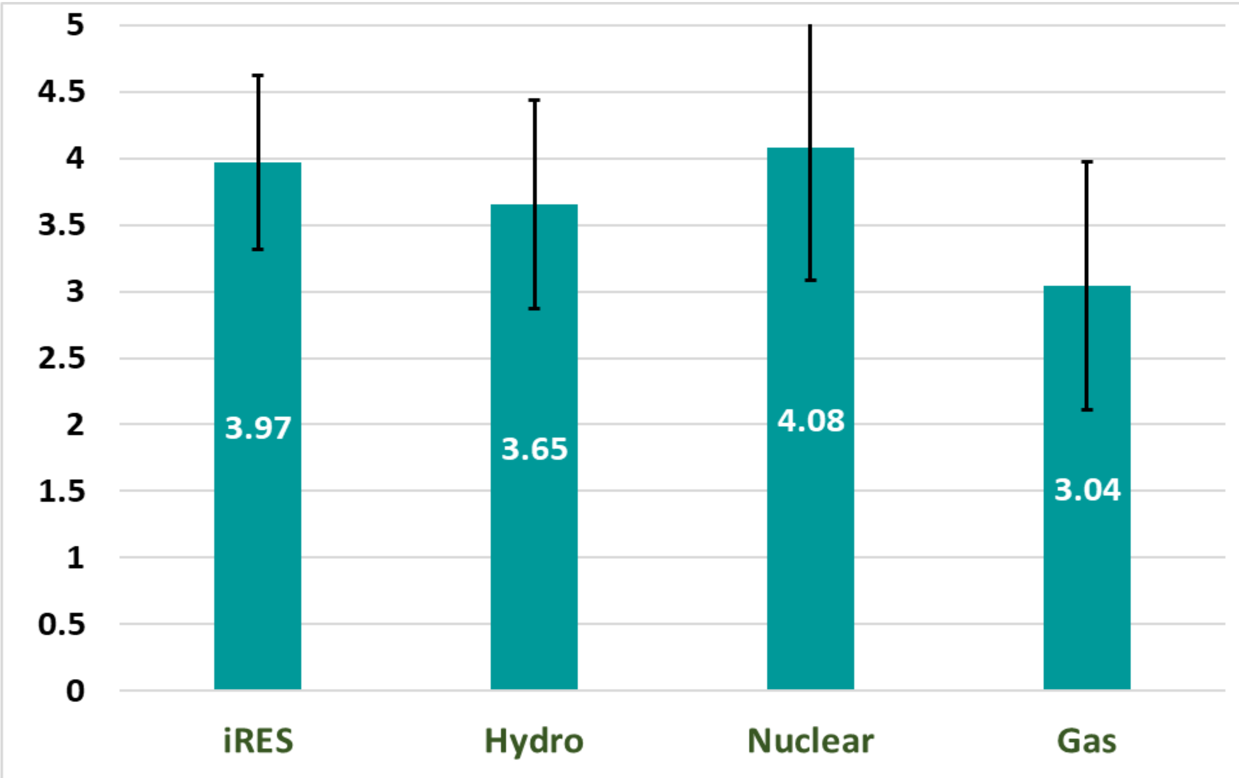


Fig. 4.1.28 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator Mitigation of accidents (S_i 1.10.2) Passive systems

- Nuclear power (score: 4.08/5) scores the highest for passive systems, reflecting the advanced design of modern nuclear reactors that incorporate passive safety features. These include systems that can automatically cool the reactor and contain radioactive materials in the event of an emergency, without needing external power or active human intervention. Such designs are critical in mitigating the risks of severe nuclear accidents. This high score reflects the effectiveness of these passive systems in enhancing the overall safety and sustainability of nuclear power.
- Intermittent renewables (score: 3.97/5) also score highly for passive safety systems, though the nature of these energy sources inherently involves fewer risks that require complex passive systems. The design of renewable energy systems often includes simple, fail-safe mechanisms, such as brakes on wind turbines or temperature regulation in solar panels, that activate automatically to prevent accidents. The simple and effective passive systems in place contribute to the overall safety of renewables, ensuring that even in the event of a malfunction, the risk of severe accidents remains low.
- Hydropower (score: 3.65/5) scores moderately for passive systems, as the inherent risks associated with water management, such as dam integrity and water flow control, require robust

passive safety features. These include spillways that automatically manage excess water levels and gravity-driven mechanisms that prevent dam failure without the need for external power or control. The score of 3.65 reflects the importance and effectiveness of passive safety systems in hydropower. While these systems are generally reliable, the potential consequences of a failure, such as flooding, mean that hydropower still requires careful monitoring and maintenance.

- Natural gas (score: 3.04/5) scores the lowest for passive safety systems, reflecting the challenges associated with managing the risks of gas leaks, explosions, and other hazards without active controls. While some passive systems, such as pressure relief valves, are in place, the nature of natural gas often requires active monitoring and intervention to ensure safety. The score of 3.04 indicates that while natural gas does incorporate some passive safety systems, these are less effective or comprehensive compared to those in nuclear, renewable, or hydropower systems. The reliance on active systems and the higher risks associated with natural gas contribute to this lower score, highlighting the need for continued development and improvement of passive safety features in the natural gas industry to enhance sustainability and safety.

These results suggest that while all energy sources benefit from passive safety systems, the complexity and effectiveness of these systems vary significantly. Nuclear power, with its high reliance on advanced passive systems, leads in this area, followed by renewables and hydropower, which have simpler but effective passive safety measures. Natural gas, due to its inherent risks and reliance on active systems, scores lower, indicating a need for further enhancement of passive safety technologies to improve sustainability and accident mitigation.

(I 1.10) Mitigation of accidents (S_i 1.10.3) Safety by design

Safety by design is the concept of making work processes and systems inherently safe by preemptively eliminating risks and hazards from them. It is a preventive approach towards safety that entails identifying potential risks involved in an existing or proposed work system and eliminating these risks by making necessary changes.

The assessment on the sustainability performances for this indicator examines how well different energy sources incorporate safety into their fundamental design. "Safety by design" refers to the intentional inclusion of safety features during the planning and construction phases of energy systems, ensuring that the technology is inherently safer and less prone to accidents throughout its operational life. The possible scores range from 1 to 5, with higher scores indicating *better integration of safety into the design of the energy systems*. The results are presented in Fig. 4.1.29.

The assessment reveals that nuclear power scores the highest at 4.41, reflecting the stringent safety design features essential for managing the high risks associated with nuclear energy. Hydropower follows closely with a score of 4.11, showing strong safety integration into the design of dams and water management systems. Intermittent renewables also score highly at 4.00, highlighting the naturally safer design of wind and solar technologies, with fewer complex safety requirements. Natural gas scores the lowest at 3.44, reflecting the challenges of designing inherently safe systems for a combustible fuel.

- Nuclear power (score: 4.41/5) scores the highest for safety by design, reflecting the rigorous standards and advanced technologies implemented in the construction of nuclear facilities. Modern nuclear reactors are designed with multiple layers of safety features, including containment structures, redundant cooling systems, and fail-safe shutdown mechanisms. These designs aim to prevent accidents and minimize risks if an incident occurs. This high score underscores the critical importance of meticulous safety planning and advanced engineering in the nuclear industry, where the potential consequences of an accident require the highest levels of precaution. The emphasis on safety by design contributes significantly to the overall sustainability and acceptability of nuclear energy.

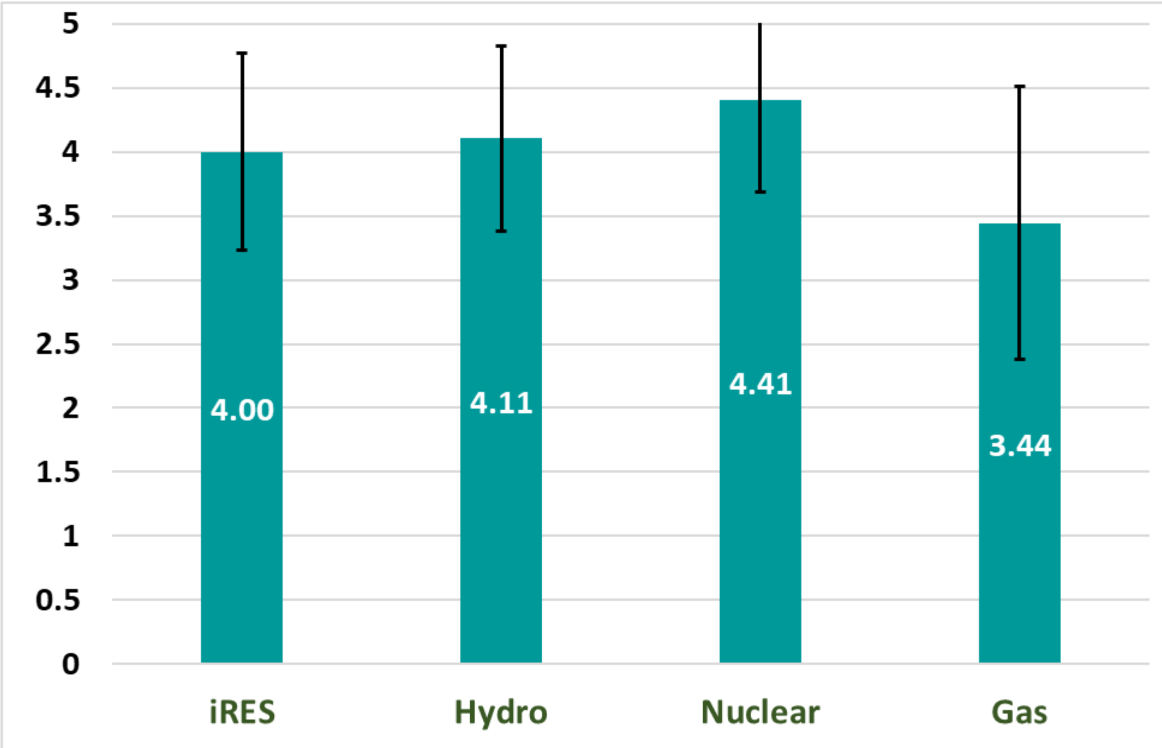


Fig. 4.1.29 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 1.10) Mitigation of accidents (S_i 1.10.3) Safety by design

- Hydropower (score: 4.11/5) also scores highly for safety by design. The design of dams, reservoirs, and water management systems includes robust safety features such as spillways, flood control mechanisms, and structural reinforcements to withstand natural events like earthquakes and floods. These safety measures are integral to preventing catastrophic failures that could result in significant environmental and human harm. The score reflects the effective integration of safety into the design of hydropower facilities. Given the potential risks associated with large-scale water management, this score indicates that hydropower systems are generally well-designed to prevent accidents. The high level of safety by design makes hydropower a reliable and sustainable energy source, provided that these systems are properly maintained and operated.

- Intermittent renewables (score: 4.00/5) score slightly lower than hydropower and nuclear but still achieve a high rating for safety by design. The inherent simplicity and low-risk nature of these technologies mean that they require fewer complex safety features. However, the design still includes essential safety mechanisms, such as automatic shutdowns in adverse weather conditions and structural safety to withstand environmental stresses. While these technologies are naturally less hazardous than others, the thoughtful integration of safety features ensures that the risks of accidents are minimized. This score highlights the robust and sustainable design of renewables, making them a safe option for energy generation.

- Natural gas (score: 3.44/5) scores the lowest in this assessment, indicating that while safety is considered in the design of natural gas systems, the inherent risks associated with the extraction, transportation, and combustion of gas pose challenges. Safety by design in natural gas facilities includes features like gas detection systems, explosion-proof equipment, and emergency shutdown procedures, but these measures are more complex and less fail-safe than those in other energy sectors. The score of 3.44 suggests that while natural gas systems incorporate important safety features, the design is not as inherently safe as those in nuclear, hydro, or renewable energy. This lower score indicates a need for ongoing improvements in the safety design of natural gas facilities to enhance sustainability.

These results emphasize that while all energy sources incorporate safety into their design, those with higher inherent risks, such as nuclear and hydropower, tend to have more complex and advanced safety designs. Renewable energy technologies are characterized by simpler, therefore resultingly safer designs, while natural gas requires ongoing advancements in safety by design to reduce risks and improve overall sustainability.

4.2 Pillar 2, Economics

(I 2.1) Capacity factor

The capacity factor calculates how efficiently a power plant or fleet of generators is operating overall. The annual capacity factor measures how many hours in the year the power plant worked as well as what proportion of its total production, as power plants occasionally operate at less than full output. The annual capacity factor of a power plant is, therefore, a measure of availability (how much hours it is available to generate electricity) and an indirect measure of the marginal cost of generation (for non-variable sources) and other characteristics such as flexibility and startup times.

The assessment on the sustainability performances for this indicator examines the efficiency and reliability of different energy sources in terms of how often they operate at their maximum potential output over time. The capacity factor is a crucial indicator because it reflects the consistency and dependability of energy production, which directly impacts the sustainability of an energy source. The possible scores range from 1 to 5, with higher scores indicating a *higher capacity factor and better overall performance in this area*. The results are presented in Fig.4.2.1.

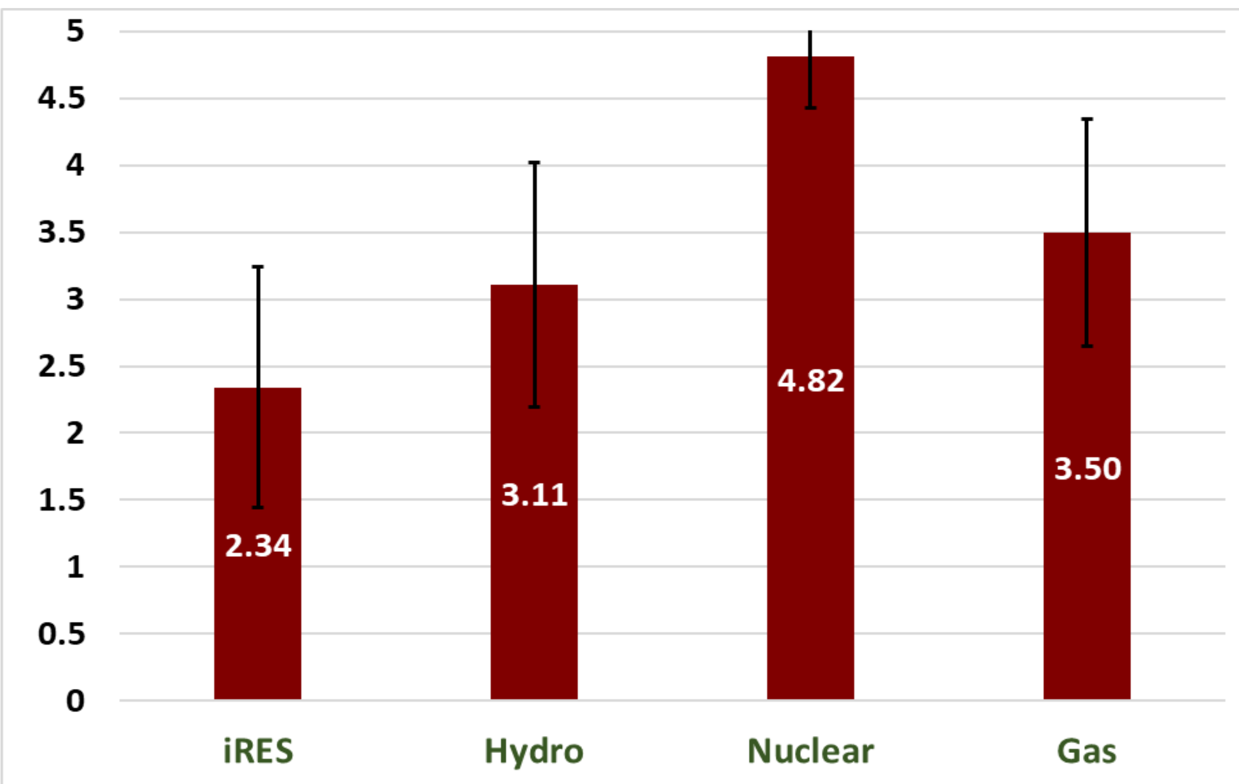


Fig. 4.2.1 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 2.1) Capacity factor

The assessment reveals that nuclear power scores the highest at 4.82, reflecting its exceptional reliability and ability to operate at high capacity over long periods. Natural gas follows with a score of 3.50, indicating its role as a flexible and reasonably reliable energy source that can adjust to varying demand. Hydropower scores 3.11, showing moderate reliability but with output variability due to environmental factors. Intermittent renewables score the lowest at 2.34, reflecting their significant variability and lower consistency in energy production.

- Nuclear power (score: 4.82/5) scores the highest for capacity factor, and in a quite consensual manner (short error bar), reflecting its ability to operate at or near full capacity for extended periods. Nuclear reactors are typically designed to run continuously, with scheduled shutdowns for maintenance and refueling being the only significant interruptions. This high-capacity factor indicates that nuclear power is a highly reliable and consistent source of energy. The score of 4.82 underscores the strong performance of nuclear power in terms of capacity factor. This near-perfect score reflects the ability of nuclear plants to provide a steady and dependable base load of energy, making it a key contributor to grid stability and energy security. The high-capacity factor also contributes to the overall sustainability of nuclear energy by maximizing the output from a given facility.
- Natural gas (score: 3.50/5) has a moderate capacity factor, with a score of 3.50. Natural gas plants are flexible and can be ramped up or down quickly to meet demand, but they do not typically operate at full capacity continuously. They are often used to complement renewable energy sources, filling in gaps when solar or wind generation is low. This flexibility, while valuable, means that natural gas plants may not achieve the high-capacity factors seen in nuclear power. The score reflects natural gas's role as a versatile and reliable energy source, but one that operates at variable capacity depending on demand.
- Hydropower (score: 3.11/5) has a capacity factor of 3.11, reflecting its variable output depending on water availability. While hydropower can be a reliable and continuous energy source, its capacity factor can be affected by seasonal changes, droughts, and water management priorities. This variability means that while hydropower is an important renewable resource, its output is less consistent than nuclear or natural gas. The capacity factor of hydropower reflects its potential to provide significant energy when water is abundant, but also highlights the challenges in maintaining consistent output. This variability impacts its role in providing a reliable energy supply, though it remains a valuable component of the renewable energy mix.
- Intermittent renewables (score: 2.34/5) score the lowest in capacity factor with a score of 2.34. These energy sources are highly dependent on environmental conditions—sunlight and wind—which can vary significantly over time. This variability leads to lower capacity factors as these energy sources cannot consistently operate at full capacity. The score highlights the inherent challenge of relying on intermittent renewables for a steady energy supply. While these sources are clean and sustainable, their lower capacity factor reflects the need for complementary energy sources or storage solutions to ensure a reliable energy supply. This lower capacity factor is a key consideration in the integration of renewables into the energy grid, necessitating strategies to mitigate their variability.

These results emphasize the importance of capacity factor in assessing the sustainability of energy sources. While nuclear power excels in providing a consistent energy supply, the variability of intermittent renewables presents challenges that must be addressed to ensure a stable energy grid. Natural gas and hydropower offer moderate reliability, playing crucial roles in balancing and supporting the integration of less consistent energy sources.

(I 2.2) Global efficiency

Energy efficiency is called the “first fuel” in clean energy transitions, as it provides some of the quickest and most cost-effective CO_2 mitigation options while lowering energy bills and strengthening energy security. Together, efficiency, electrification, behavioral change, and digitalization shape global energy intensity – the amount of energy required to produce a unit of GDP, a key measure of energy efficiency of the economy.

Energy efficiency is the single largest measure to avoid energy demand in the Net Zero Emissions by 2050 Scenario [4]. Furthermore, most efficiency measures result in cost savings to consumers, lowering energy bills and helping cushion the effects of unexpected price spikes, such as occurred after Russia’s invasion of Ukraine.

The assessment on the sustainability performances for this indicator examines how effectively different energy sources convert their available energy into usable power. Global efficiency considers the entire energy production process, including conversion losses, operational efficiency, and the overall effectiveness of the energy source in delivering power to the grid. The possible scores range from 1 to 5, with higher scores indicating better efficiency in converting energy into usable electricity. The results are presented in Fig. 4.2.2.

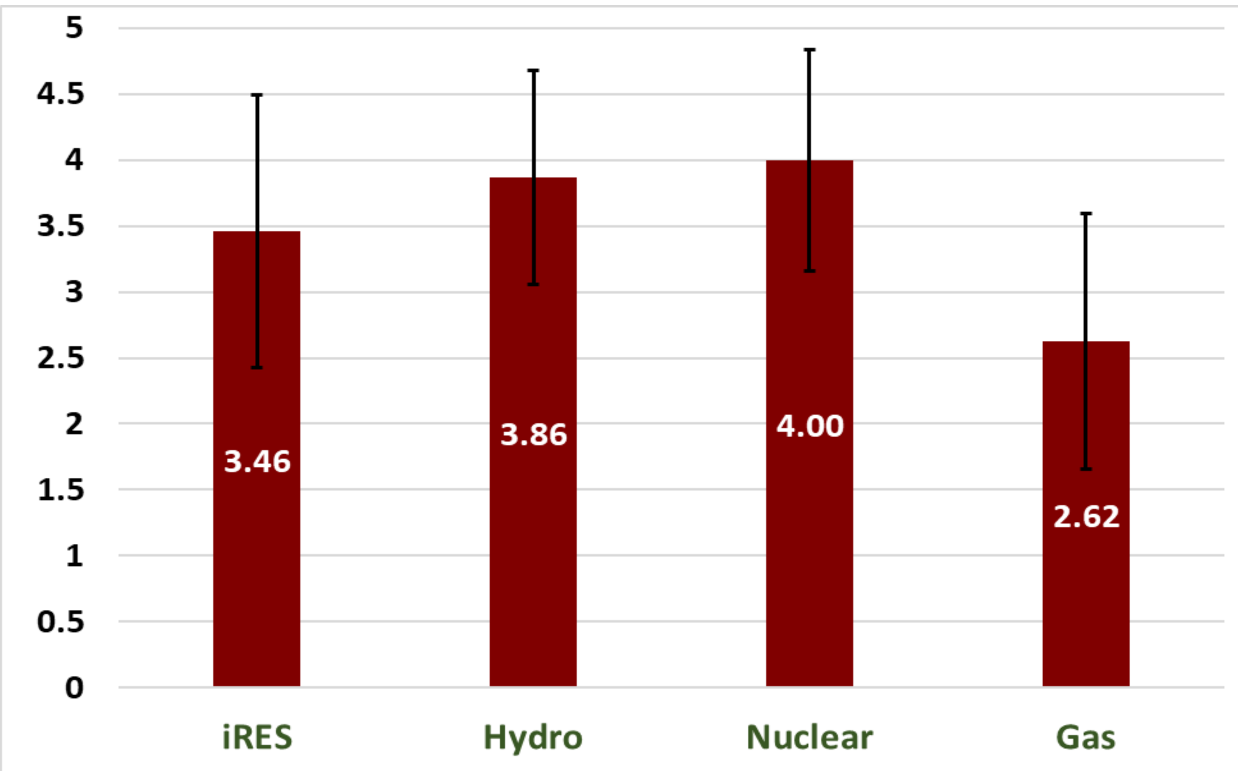


Fig. 4.2.2 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 2.2) Global efficiency

The assessment reveals that nuclear power scores the highest at 4.00, indicating its excellent global efficiency and ability to convert a significant portion of its fuel into electricity. Hydropower follows closely with a score of 3.86, reflecting its efficient conversion of potential energy from water into power. Intermittent renewables score a respectable 3.46, with improvements in technology helping to enhance their efficiency, despite challenges related to variability. Natural gas scores the lowest at 2.69, reflecting lower overall efficiency due to losses in the extraction, transport, and generation processes, with some penalties due to the current variable regimes complementing iRES.

- Nuclear power (score: 4.00/5) achieves the highest score for global efficiency, reflecting its ability to convert a high percentage of nuclear fuel's energy into electricity. Nuclear reactors are designed to operate with high thermal efficiency, and despite the complex processes involved in nuclear fission, modern reactors can achieve substantial conversion rates, minimizing energy losses. The score of 4.00 highlights the strong performance of nuclear power in terms of global efficiency. This high efficiency contributes to the sustainability of nuclear energy, as more electricity can be generated from a given amount of fuel. The efficient use of nuclear fuel not only supports energy security but also reduces the environmental impact associated with fuel extraction and waste management.
- Hydropower (score: 3.86/5) scores highly for global efficiency, reflecting the effective conversion of potential energy from stored water into electricity. The efficiency of hydropower systems is largely dependent on the height of the water drop (head) and the flow rate. Well-designed hydroelectric plants can achieve very high conversion efficiencies, with minimal losses during the process. The score of 3.86 indicates that hydropower is a highly efficient means of generating electricity. Its strong performance in global efficiency makes it one of the most sustainable and reliable renewable energy sources.
- Intermittent renewables (score: 3.46/5) score a moderate 3.46 in global efficiency. The efficiency of these energy sources is influenced by factors such as location, technology, and weather conditions. While modern solar panels and wind turbines have improved in efficiency, the variability in power generation and the need for storage or backup systems can reduce overall efficiency. The score of 3.46 reflects the decent but variable efficiency of intermittent renewables. While advances in technology have improved the efficiency of converting sunlight and wind into electricity, the intermittent nature of these sources means that they cannot always operate at peak efficiency. Nevertheless, they are important contributors to a sustainable energy mix, particularly when paired with energy storage or other forms of backup power.
- Natural gas (score: 2.69/5) has, in the opinion of the respondents, the lowest score for global efficiency, at 2.69. While natural gas plants can be quite efficient, particularly combined cycle plants that capture waste heat for additional power generation, the overall efficiency is lower compared to nuclear and hydropower. Factors such as energy losses during extraction, transport, and combustion contribute to this lower score. More important, in the last decade, the gas plants were usually operated to balance the intermittency of solar and wind production.

These results highlight the importance of global efficiency in assessing the sustainability of different energy sources. Higher efficiency not only means better use of resources but also a lower environmental impact. While nuclear and hydropower excel in this area, intermittent renewables offer good performance with ongoing improvements, and natural gas, though less efficient, remains a key player due to its flexibility and ability to provide reliable power.

(I 2.3) Cost (S_i 2.3.1) Cost of the investment (capital cost)

The costs for generating electricity are usually divided into capital investment costs, operating and maintenance costs, and fuel costs. The indicator "Cost of the investment (capital cost)" refers to the total upfront expenses required to develop and build an energy project, including the costs of planning, permitting, purchasing, and installing all necessary equipment and infrastructure. This indicator is crucial for understanding the financial commitment and economic feasibility of different energy alternatives.

The capital investment costs include both the overnight (capital) cost per unit of installed capacity and the costs of financing, which depend on the duration of construction, the construction expenditure flow, and the cost of capital.

Generally, the assessment on this indicator examines the initial financial outlay required to build and deploy various energy generation technologies. This indicator is crucial because it reflects the economic feasibility and attractiveness of different energy sources. The possible scores range from 1 to 5, with higher scores indicating *lower capital costs and thus more favorable investment conditions*. The results are presented in Fig. 4.2.3.

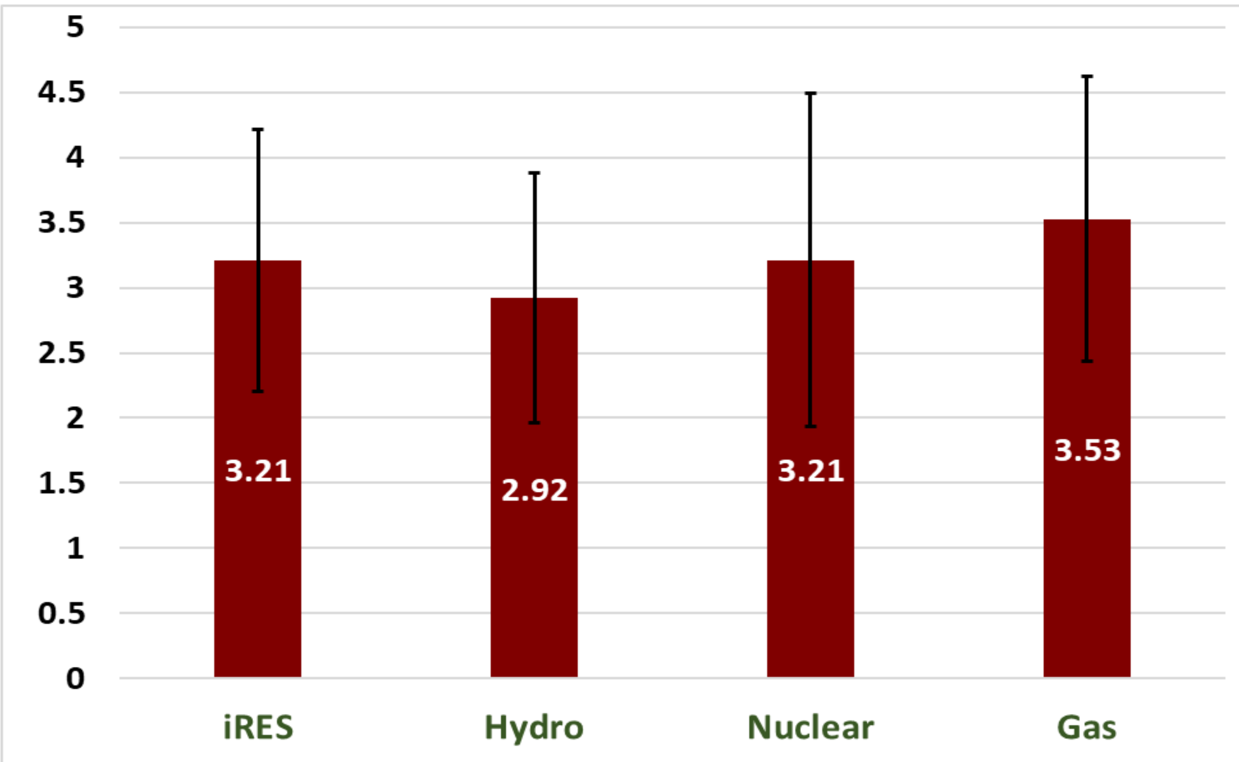


Fig. 4.2.3 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 2.3) Cost (S_i 2.3.1) Cost of the investment (capital cost)

The assessment shows that natural gas scores the highest at 3.53, reflecting its relatively low capital cost, which makes it an attractive option for quick and cost-effective energy generation. Intermittent renewables and nuclear power both score 3.21, indicating moderate capital costs. While renewables benefit from declining costs, nuclear power's high initial expense is balanced by its long-term benefits. Hydropower scores the lowest at 2.92, highlighting the substantial capital investment required to develop hydroelectric projects.

- Natural Gas (score: 3.53/5) scores the highest in terms of capital cost, indicating that it generally requires a lower upfront investment compared to other energy sources. The infrastructure for natural gas plants is relatively simple and cost-effective to build, and the technology is well-established, which contributes to its higher score. The score of 3.53 suggests that natural gas is an attractive option for investors and governments looking to add generating capacity quickly and at a lower initial cost. This lower capital cost makes natural gas a flexible and economically viable option, especially for countries needing to expand their energy supply rapidly. However, while the initial investment is low, ongoing fuel costs and environmental concerns need to be considered.

- Intermittent renewables (score: 3.21/5) share the same score as nuclear at 3.21, reflecting a more moderated performance in the capital cost compared with natural gas technology. The costs for renewables have been declining over the years due to technological advancements and economies of scale. However, the initial capital investment is still significant, particularly for large-scale solar farms or wind parks. The score of 3.21 for intermittent renewables indicates that while the capital costs are not the lowest, they are becoming increasingly competitive. This moderate score reflects the balance between the initial investment required and the long-term benefits of low operational costs and no fuel expenses. Additionally, as technology continues to improve and deployment scales up, the capital costs for renewables are expected to continue decreasing, further enhancing their sustainability profile.
- Nuclear power (score: 3.21/5) scores 3.21 for capital cost, indicating that it requires a significant initial investment. Of note, this rating is dissensual (longer error bar), indicating differential rater sensitivity or knowledge on this aspect for nuclear. Building a nuclear power plant involves complex engineering, rigorous safety measures, and long lead times, all of which contribute to high upfront costs. However, the long operational life and the potential for high energy output can justify the initial expense. The score of 3.21 reflects the substantial capital investment required for nuclear power. While the upfront costs are high, the long-term returns in terms of reliable and high-capacity energy generation can make nuclear power a worthwhile investment. The high capital costs are a barrier to entry, but for nations and companies that can afford the investment, nuclear power offers a sustainable, low-carbon energy source with significant long-term benefits.
- Hydropower (score: 2.92/5) has the lowest score at 2.92, indicating that it typically has the highest capital costs among the assessed energy sources. Building hydroelectric dams requires significant investment in infrastructure, including large-scale construction, land acquisition, and environmental mitigation efforts. These high upfront costs can be a barrier to hydropower development, particularly in less economically developed regions. Despite the high initial investment, hydropower can offer long-term benefits, including low operational costs and the ability to generate substantial amounts of renewable energy. However, the financial burden of these projects can make them less attractive to investors, particularly in areas where the economic and environmental costs are higher.

These results describe the understandings of the respondents on the level of attraction of different energy technology considering the capital cost as a factor determining the feasibility of energy projects. While lower capital costs can make a technology more accessible and easier to deploy, the long-term sustainability and environmental impacts must also be considered. Natural gas, with its low capital costs, remains a popular choice, but as renewable technologies become more affordable, they are increasingly competitive. Nuclear and hydropower, despite their high initial costs, offer significant long-term benefits that can justify the investment under the right circumstances.

(I 2.3) Cost (S_i 2.3.2) Cost of operation (including fueling and maintenance)

The costs for generating electricity are usually divided into capital investment costs, operating and maintenance costs (O&M) and fuel costs. The cost of operation includes both the O&M costs and fuel costs. However, in most approaches for generating electricity costs calculation these types of costs are treated separately.

O&M costs are usually divided into variable O&M costs, including those that depend on the amount of energy generated, and fixed O&M costs, including those that do not depend on the energy generated each year (e.g. staff salaries, auxiliary equipment and materials purchasing, refurbishment of buildings and equipment, non-fuel waste management, etc.). Usually variable O&M costs are proportional to the annual electricity output. Miscellaneous O&M costs include items such as public relations, training, rents, and travel. It also includes liability insurance and the fixed charges for the working capital to pay for items in the O&M category.

The assessment on the sustainability performances for this indicator examines the ongoing expenses associated with operating, fueling, and maintaining different energy generation technologies. This indicator is crucial in understanding the long-term economic viability and sustainability of each energy source. The possible scores range from 1 to 5, with higher scores indicating *lower operational costs*, making the energy source more economically sustainable in the long run. The results are presented in Fig. 4.2.4.

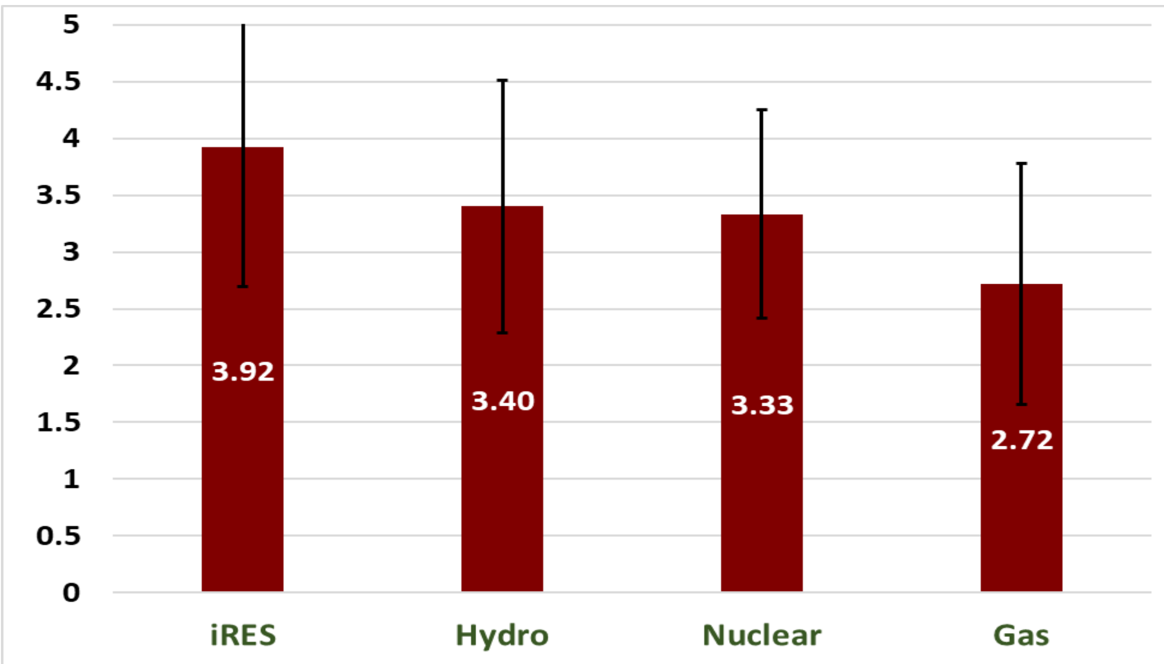


Fig. 4.2.4 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 2.3) Cost (S_i 2.3.2) Cost of operation (including fueling and maintenance)

The assessment reveals that intermittent renewables score the highest at 3.92, indicating their low operational costs, which enhances their long-term economic sustainability. Hydropower follows with a score of 3.40, reflecting moderate operational costs, primarily due to maintenance of large infrastructure. Nuclear power scores 3.33, highlighting the relatively high costs associated with fuel, maintenance, and safety measures. Natural gas scores the lowest at 2.72, reflecting its significant operational costs driven by continuous fuel purchases and maintenance requirements.

- Intermittent renewables (score: 3.92/5) score the highest at 3.92, reflecting their low operating costs. Once installed, these technologies have zero fuel costs because they rely on natural resources—sunlight and wind—that are free. Maintenance costs are also relatively low, particularly for solar power, although wind turbines can require more regular upkeep. The high score of 3.92 indicates that intermittent renewables are very cost-effective to operate. As technology advances and maintenance practices improve, these costs are expected to decrease even further, enhancing the financial attractiveness of renewables over time.

- Hydropower (score: 3.40/5) has a score of 3.40, indicating moderate operational costs. Hydroelectric plants have low fuel costs since they rely on the flow of water to generate electricity. However, maintenance of the infrastructure, such as dams, turbines, and reservoirs, can be significant, particularly in the long term. The operational costs also include management of water flow, ensuring safety, and mitigating environmental impacts. However, given the longevity and reliability of hydropower plants, these costs are manageable, making hydropower a stable and sustainable energy source from an operational cost perspective.
- Nuclear power (score: 3.33/5) scores 3.33, indicating relatively higher operational costs compared to renewables and hydropower. The costs of fueling and maintaining a nuclear power plant are significant due to the complexity of the technology, the need for stringent safety measures, and the handling of nuclear fuel. Additionally, the costs associated with waste management and regulatory compliance contribute to the overall operational expenses. While nuclear plants can operate for many years, the costs of fuel fabrication, safety protocols, and waste disposal remain important. Despite these costs, the consistent and large-scale energy output of nuclear plants can justify the expenses, especially in regions prioritizing low-carbon energy.
- Natural gas (score: 2.72/5) has the lowest score at 2.72, indicating the highest operational costs among the assessed energy sources. The primary reason for this is the ongoing cost of fuel, as natural gas must be continuously purchased and supplied to the power plants. Additionally, maintenance costs can be significant, particularly in older plants or those that operate in areas with stringent environmental regulations. The score of 2.72 suggests that natural gas, while relatively low in capital cost, incurs higher operational costs due to the continuous need for fuel and maintenance. These ongoing expenses can make natural gas less attractive from a long-term financial sustainability perspective, especially as fuel prices fluctuate and environmental regulations become stricter. However, the flexibility and reliability of natural gas in providing consistent power can still make it a viable option for many energy systems.

These results suggest the importance of considering not just the initial investment but also the ongoing costs when evaluating the sustainability of different energy sources. While natural gas may offer lower upfront costs, its high operational expenses can make it less economically sustainable over time. In contrast, renewables, with their low operational costs, present a financially attractive option for long-term energy generation, especially as technology and efficiency continue to improve.

(I 2.3) Cost, (S_i 2.3.3) Cost of decommissioning (including environmental remediation)

Decommissioning is a normal part of the lifecycle of almost all industrial facilities. When the facility no longer serves a useful social or economic purpose, it needs to be dismantled and the site made available for other uses. Requirements for decommissioning should be considered during design and planning of facilities. The decommissioning plan and associated cost estimates need to be prepared in advance, to ensure that sufficient financial resources are available.

Environmental remediation is the process of removing contaminants from sites (buildings, soil, groundwater, sediment, or surface water) that have been polluted due to industrial, manufacturing, mining, and commercial activities. Remediation involves an all-encompassing step process of land restoration from detection, investigation, assessment, determination of remedial measure, actual clean-up, to site redevelopment.

The assessment on this indicator examines the financial and environmental costs associated with dismantling and safely closing energy generation facilities at the end of their operational life. This indicator is important because decommissioning can be a significant financial burden, and improper remediation can lead to long-term environmental damage. The possible scores range from 1 to 5, with higher scores indicating *lower decommissioning costs and more effective environmental remediation*. The results are presented in Fig. 4.2.5.

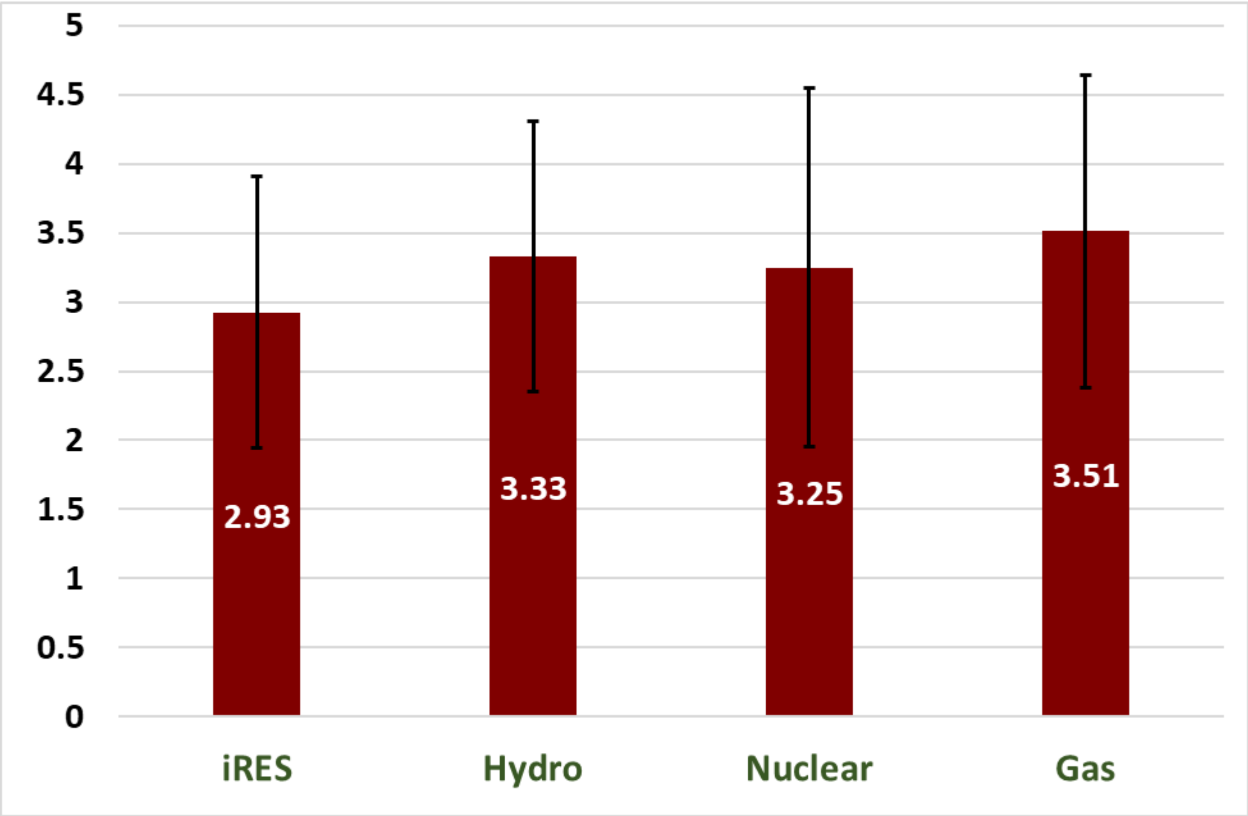


Fig. 4.2.5 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 2.3) Cost, (S_i 2.3.3) Cost of decommissioning (including environmental remediation)

The assessment shows that natural gas scores the highest at 3.51, indicating that it has the lowest decommissioning costs, making it a more economically sustainable option in terms of end-of-life considerations. Hydropower follows with a score of 3.33, reflecting moderate decommissioning costs but significant environmental remediation challenges. Nuclear power scores 3.25, highlighting the high costs and complexity of safely decommissioning and remediating nuclear sites. Intermittent renewables score the lowest at 2.93, indicating higher-than-expected decommissioning costs due to the challenges of material disposal and recycling.

- Natural gas (score: 3.54/5) scores the highest at 3.51, reflecting relatively lower decommissioning costs compared to other energy sources. The infrastructure for natural gas plants is generally less complex, and the process of decommissioning is straightforward, involving the dismantling of equipment and the safe disposal of materials. Environmental remediation is also more manageable, as natural gas facilities typically have a smaller environmental footprint than other energy sources. The lower costs associated with decommissioning and environmental remediation contribute to its overall sustainability, making it a favorable choice in terms of end-of-life considerations. However, it's important to consider that while decommissioning may be cost-effective, the environmental impact during the operational phase still needs to be accounted for.

- Hydropower scores 3.33, reflecting moderate decommissioning costs. Decommissioning a hydroelectric facility can be complex and costly, particularly when it involves the removal of large dams, which may require extensive environmental remediation. The process can also have significant ecological impacts, as it often involves restoring natural river flows and managing sediment buildup. The score suggests that while hydropower is generally sustainable, the decommissioning phase can be challenging and expensive. The need for substantial environmental remediation, such as restoring ecosystems and mitigating long-term impacts on water bodies, contributes to these costs. Despite this, the long operational life of hydropower plants can offset some of these decommissioning costs over time.
- Nuclear power scores 3.25, indicating relatively high decommissioning costs – although this view is not consensual (longer error bar), possibly indicating a range of knowledge on this issue among raters. Decommissioning a nuclear power plant is a complex and lengthy process due to the need to safely handle and dispose of radioactive materials. Environmental remediation is also a significant concern, as the site must be thoroughly decontaminated to prevent long-term environmental and health risks. These processes are governed by strict regulatory standards, which add to the cost. The long timeframes and high costs can be a significant burden. However, the stringent regulations and protocols in place help ensure that these processes are managed carefully, minimizing the environmental impact and long-term risks.
- Intermittent renewables score the lowest at 2.93, indicating relatively higher decommissioning costs. While the physical dismantling of renewable energy infrastructure is generally straightforward, the disposal and recycling of materials, such as solar panels and wind turbine blades, can be challenging and costly. Additionally, the environmental impact of disposing of or recycling these materials must be carefully managed to avoid long-term environmental damage. The score of 2.92 suggests that decommissioning intermittent renewable energy facilities can be more expensive and complex than initially expected. As the renewable energy sector grows, improving recycling technologies and practices will be crucial to reducing these decommissioning costs and enhancing the overall sustainability of renewables.

These results suggest the importance of considering decommissioning and environmental remediation costs in the overall sustainability assessment of energy sources. While natural gas and hydropower may be more cost-effective to decommission, nuclear power and renewables face greater challenges that need to be addressed to improve their long-term sustainability. For renewables, particularly, advancements in recycling technologies and practices will be key to reducing decommissioning costs and enhancing their sustainability profile.

(I 2.4) Cost for system integration, (S_i 2.4.1) Maneuverability

The indicator "Cost for System Integration, Maneuverability" examines the expenses associated with integrating an energy technology into the existing energy system with a focus on its ability to adapt to varying operational conditions. This includes the technology's flexibility in responding to changes in energy demand and supply, and its capacity to operate efficiently under different conditions.

Maneuverability is the capability of an energy technology to adjust its output, operation, or behavior in response to varying energy demands, supply conditions, and operational requirements. It reflects how well a system can "maneuver" or adapt to dynamic conditions in the energy grid. Maneuverability refers to the flexibility of the energy source to ramp up or down quickly, which is essential for maintaining grid stability. The maneuverability is restricted to the direct control of the system, and do not consider load following by cogeneration, storage, turbine by-pass, etc.

The assessment on the sustainability performances for this indicator examines how easily and cost-effectively each energy source can be integrated into the power grid, particularly in terms of its ability to adjust output in response to changing demand. The possible scores range from 1 to 5, with higher scores indicating *better maneuverability and lower costs for system integration*. The results are presented in Fig. 4.2.6.

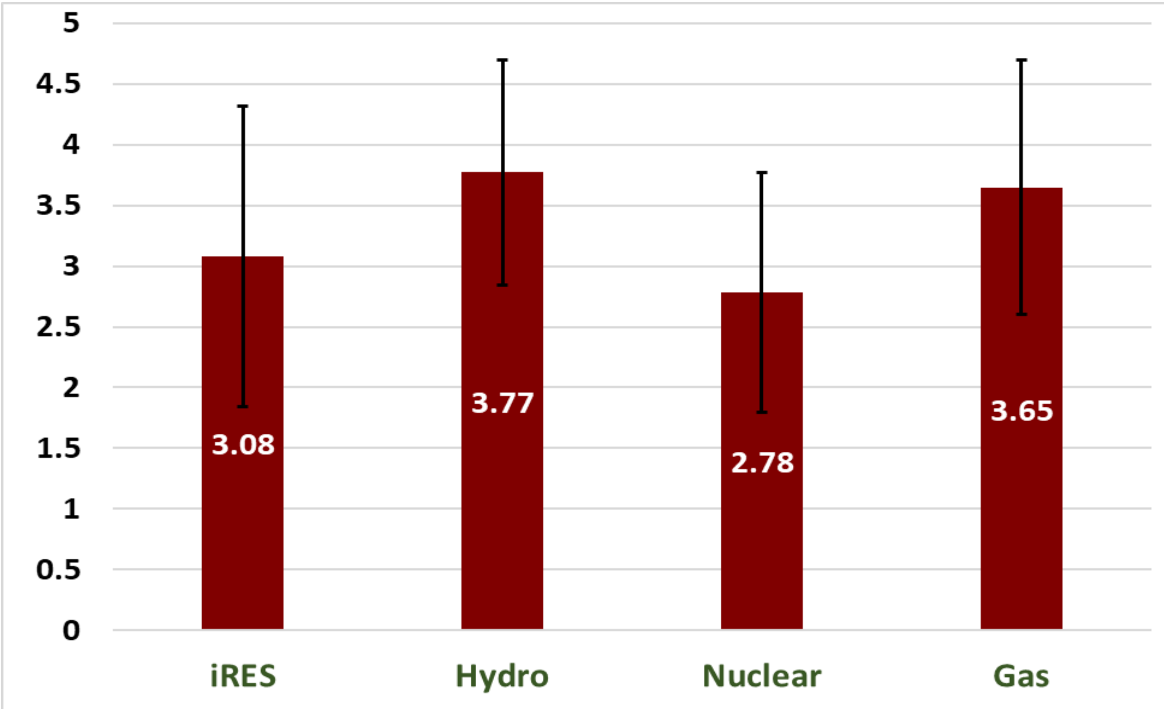


Fig. 4.2.6 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 2.4) Cost for system integration, (S_i 2.4.1) Maneuverability

The assessment reveals that hydropower scores the highest at 3.77, indicating excellent maneuverability and low system integration costs, making it a highly sustainable option for flexible grid management. Natural gas follows closely with a score of 3.65, reflecting its high flexibility and moderate costs, making it valuable for balancing supply and demand. Intermittent renewables score 3.08, indicating moderate integration costs due to their variable output, which requires additional infrastructure to manage. Nuclear power scores the lowest at 2.78, reflecting its limited maneuverability and higher integration costs, particularly in systems that demand more dynamic responsiveness.

- Hydropower (score: 3.77/5) scores the highest at 3.77, reflecting its excellent maneuverability and relatively low integration costs. Hydropower plants can quickly adjust their output to meet fluctuations in demand, making them highly valuable for grid stability. The ability to store water and release it as needed allows hydropower to respond effectively to both short-term and long-term changes in electricity demand. The high score indicates that hydropower is an extremely flexible and cost-effective option for system integration. Its ability to provide both base load and peak load power, along with its quick response times, makes hydropower a reliable and economically sustainable choice for grid operators. This flexibility reduces the need for additional backup systems, thereby lowering overall system costs.
- Natural gas (score: 3.65/5) also scores well, with a score of 3.65, reflecting its high maneuverability and moderate integration costs. Natural gas plants can ramp up or down relatively quickly, making them suitable for balancing the grid and accommodating fluctuations

in supply and demand. This flexibility is especially valuable in systems with a high penetration of intermittent renewables, as natural gas can provide a reliable backup when renewable output is low. The score of 3.65 suggests that natural gas is a flexible and cost-effective option for system integration. Its ability to provide rapid response to changes in demand makes it an important tool for maintaining grid stability, especially in energy systems with large penetration of iRES. However, the reliance on fossil fuels and associated emissions remains a consideration for long-term sustainability.

- Intermittent renewables (score: 3.08/5) score 3.08, reflecting moderate integration costs and limited maneuverability. While these energy sources are clean and sustainable, their output is variable and dependent on weather conditions. This variability can make it challenging to integrate them into the grid without additional infrastructure, such as energy storage systems or backup power sources, to manage fluctuations. The score of 3.08, although not a highly consensual one compared to the means obtained here by the other technologies (larger error interval), indicates that while intermittent renewables are increasingly important in energy systems, their variability poses challenges for grid integration. The need for supplementary technologies, like batteries or flexible gas plants, increases the overall cost of integration. It seems the respondents assessed the iRES considering storage as a part of maneuverability, contrary to the current definition.

- Nuclear power (score: 2.78/5) scores the lowest at 2.78, indicating relatively low maneuverability and higher integration costs. Nuclear plants are designed to operate continuously (economic motivations) at a steady output, making them less flexible in adjusting to short-term changes in demand. While they are excellent for providing base load power, their limited ability to ramp up or down quickly can be a disadvantage in a modern grid that requires more dynamic responsiveness. The score of 2.78 (showing relative consensus when compared to the standard deviation seen here for reflects the challenges associated with integrating nuclear power into modern, flexible energy grids. Although nuclear energy provides a stable and reliable source of power, its limited maneuverability can necessitate additional investments in grid management and backup systems, increasing the overall cost of integration. To enhance its sustainability in future energy systems, nuclear power may need to be complemented with more flexible energy sources.

These results highlight the importance of considering maneuverability and integration costs when assessing the sustainability of different energy sources. While hydropower and natural gas provide valuable flexibility for grid stability, intermittent renewables require additional infrastructure to manage variability, and nuclear power faces challenges due to its limited maneuverability. As energy systems evolve, improving the integration of renewables and enhancing the flexibility of nuclear power could be key to achieving more sustainable energy grids.

(I 2.4) Cost for system integration, (S_i 2.4.2) Load following

Load following refers to the ability of a power plant or energy source to increase or decrease its generation output dynamically in response to changes in electrical load or demand from the grid. The goal is to ensure that supply matches demand at all times, maintaining grid stability and reliability.

Load following means adjustable output, the possibility to modulate the generation output in real-time to align with fluctuating electricity demand. Load following may be achieved partially by maneuverability, but also by co-generation, storage, etc.

The assessment on the sustainability performances for this indicator examines how different energy sources can adjust their output to follow changes in electricity demand. Load following refers to the ability of a power plant to increase or decrease its output in response to fluctuations in energy demand, which is crucial for maintaining grid stability. The possible scores range from 1 to 5, with higher scores indicating *lower costs associated with effectively following load changes*. The results are presented in Fig. 4.2.6.

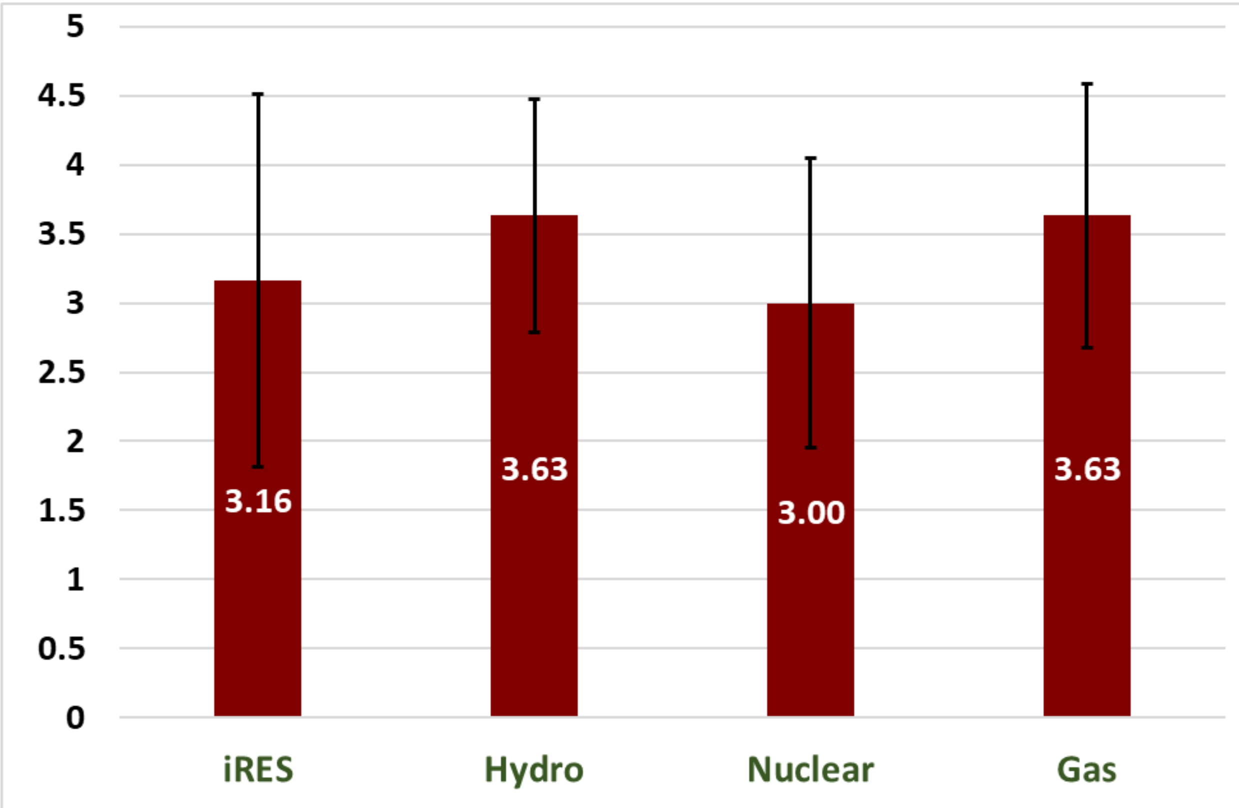


Fig. 4.2.7 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 2.4) Cost for system integration, (S_i 2.4.2) Load following

The assessment reveals that hydropower and natural gas both score 3.63, indicating strong capabilities for load following with moderate integration costs. Their ability to adjust output quickly helps maintain grid stability and supports efficient energy management. Intermittent renewables score 3.16, reflecting moderate effectiveness in load following due to their variable nature and the need for additional support from backup systems or storage solutions. Nuclear power scores the lowest at 3.00, highlighting its limited ability to follow load changes and the associated higher integration costs.

- Hydropower (score: 3.63/5) scores 3.63, reflecting its strong capability for load following with moderate integration costs. Hydropower plants can quickly adjust their output by varying the flow of water through turbines, which allows them to respond efficiently to changes in demand. This flexibility is particularly valuable for managing daily and seasonal variations in energy consumption. The score of 3.63 indicates that hydropower is effective and relatively cost-efficient for load following. Its ability to rapidly adjust output helps stabilize the grid and reduce the need for additional backup power sources. The moderate costs associated with this capability are offset by the operational benefits of integrating hydropower into energy systems that require flexible load management.

- Natural gas (score: 3.63/5) also scores 3.63, indicating similar effectiveness in load following as hydropower. Natural gas plants can adjust their output relatively quickly, which makes them well-suited for responding to fluctuations in demand. This flexibility helps to balance the grid, especially when renewable sources are variable. The score suggests that natural gas is highly effective for load following, with costs comparable to those of hydropower. Its ability to ramp up or down efficiently supports grid stability and complements intermittent renewable sources. While natural gas provides valuable flexibility, it is important to consider its environmental impact and fuel costs over the long term.

- Intermittent renewables (score: 3.16/5) score 3.16, reflecting moderate effectiveness in load following with associated integration costs. These sources are variable and dependent on weather conditions, which makes load following challenging. The score of 3.16 indicates they are less effective compared to hydropower and natural gas. The variability in their output necessitates the integration of backup systems or energy storage solutions, which can increase overall system costs. Advances in energy storage and grid management technologies are crucial for improving the load-following capabilities of renewable sources. Of note however, the rating is quite dissensual (longer error bar), possibly suggesting that some respondents may consider storage capacity as a source of load following, despite the definition provided for this indicator.

- Nuclear power (score: 3.00/5) scores the lowest at 3.00, indicating lower effectiveness in load following with relatively higher integration costs. Nuclear plants are designed to operate at a constant output, making them less flexible in adjusting to rapid changes in demand. While they provide a stable base load, they are not well-suited for rapid load following. The score of 3.00 reflects the limitations of nuclear power in load following. It seems the respondents, did not considered the Small Modular Reactors (with better load following capabilities), and no cogeneration, or thermal storage of the energy.

These results underscore the importance of considering load-following capabilities when evaluating the sustainability of different energy sources. While hydropower and natural gas provide effective and cost-efficient load following, intermittent renewables and nuclear power face challenges that impact their integration into dynamic energy systems. Improving energy storage and grid management technologies will be essential for enhancing the load-following capabilities of intermittent renewables and optimizing the overall sustainability of energy systems.

(I 2.4) Cost for system integration, (S_i 2.4.3) Stability

"Cost for System Integration, Stability" refers to the financial expenses involved in integrating an energy technology into the existing energy grid in a way that ensures and enhances grid stability. This includes both the direct costs of implementing stabilization measures and the indirect costs related to maintaining a stable and reliable energy supply.

The assessment on the sustainability performances for this indicator examines how different energy sources contribute to grid stability and the associated costs of integrating them into the power system. Stability refers to the ability of an energy source to maintain a steady supply and support the overall reliability of the grid, particularly in terms of frequency and voltage control. The possible scores range from 1 to 5, with higher scores indicating *better stability and lower integration costs*. The results are presented in Fig. 4.2.8.

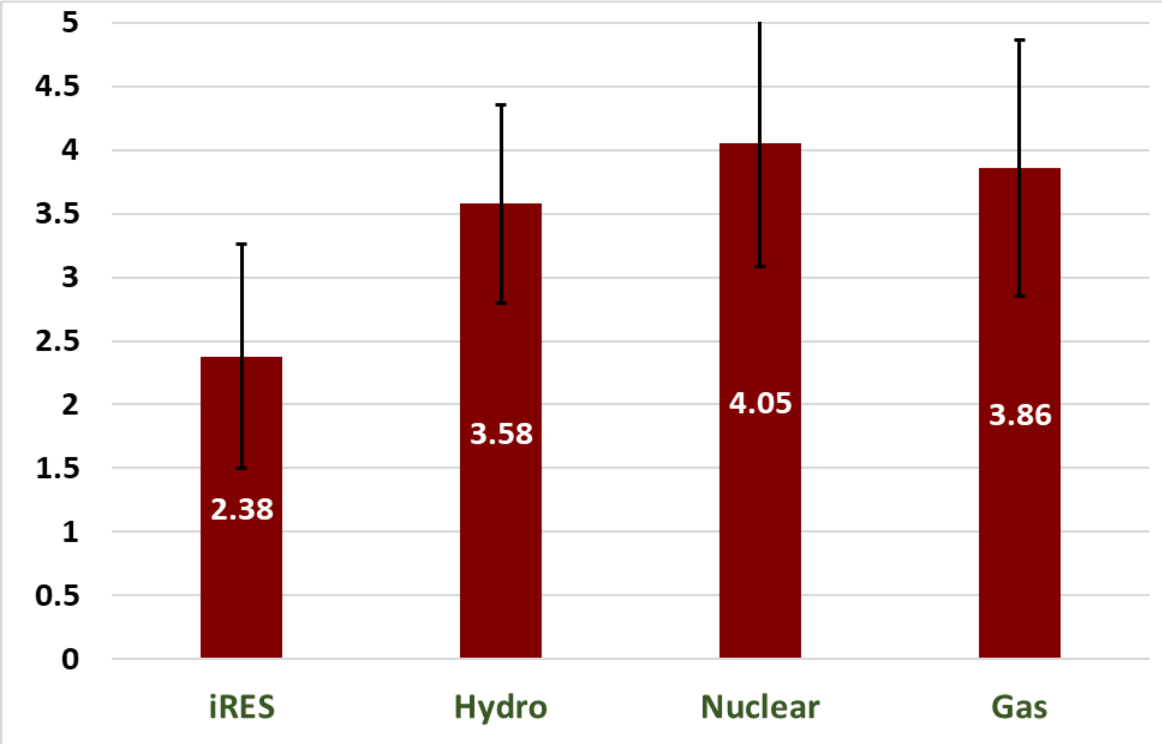


Fig. 4.2.8 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 2.4) Cost for system integration, (S_i 2.4.3) Stability

The assessment reveals that nuclear power scores the highest at 4.05, indicating its strong contribution to grid stability and relatively low associated integration costs. Natural gas follows with a score of 3.86, reflecting its good stability and manageable costs, though it relies on fossil fuels. Hydropower scores 3.58, highlighting its ability to support grid stability with moderate integration costs. Intermittent renewables score the lowest at 2.38, reflecting their challenges in maintaining grid stability and the higher costs associated with managing their variability.

- Nuclear power (score: 4.05/5) scores the highest at 4.05, reflecting its strong contribution to grid stability with relatively low integration costs. Nuclear plants provide a consistent and reliable base load of electricity, which helps maintain grid frequency and voltage stability. Their high-capacity factor and steady output make them a stable and dependable source of power for the grid. Its consistent output minimizes fluctuations and helps maintain a steady supply, reducing the need for additional stabilization measures. The relatively low integration costs associated with nuclear power further enhance its sustainability profile, making it a valuable component of a stable energy grid.

- Natural gas (score: 3.86/5) scores 3.86, showing a good level of stability with moderate integration costs. Natural gas plants can respond quickly to changes in demand and provide backup power to support grid stability. Their flexibility in adjusting output helps to manage fluctuations and maintain grid reliability, although they are not as consistent as nuclear power. The score of 3.86 reflects that natural gas contributes effectively to grid stability, with costs that are manageable. While it provides important flexibility and backup power, its reliance on fossil fuels and associated emissions are factors to consider. Overall, natural gas plays a significant role in maintaining grid stability but should be complemented with other low-emission sources for a more sustainable energy mix.

- Hydropower (score: 3.58/5) scores 3.58, indicating good stability with moderate integration costs. Hydropower plants can help stabilize the grid through their ability to adjust output and provide ancillary services like frequency regulation. The storage capabilities of pumped storage hydro plants further enhance their role in grid stability. The score suggests that hydropower is a valuable asset for grid stability, offering both reliable power and the ability to respond to changes in demand. The integration costs are reasonable, and hydropower's contribution to maintaining grid stability is significant.

- Intermittent renewables (score: 2.38/5) score the lowest at 2.38, reflecting challenges with grid stability and higher integration costs. The variable nature of these sources can lead to fluctuations in power supply, which can impact grid stability. Integrating intermittent renewables often requires additional infrastructure, such as energy storage or backup power sources, to manage these fluctuations and ensure a reliable supply. The low score indicates that intermittent renewables present significant challenges for grid stability, primarily due to their variability and the associated costs of integrating them into the grid. While they are essential for reducing carbon emissions, their contribution to grid stability is limited without complementary technologies or flexible power sources. As the share of renewables increases, advancements in energy storage and grid management will be crucial for improving their stability performance and reducing integration costs.

These results reflect the cost of system integration considering stability of the energy grid. Nuclear power and natural gas provide significant benefits in terms of grid stability, while hydropower offers a reliable option with moderate costs. Intermittent renewables, despite their environmental benefits, require additional measures to ensure grid stability, highlighting the need for continued innovation in energy storage and grid management technologies to enhance their integration and overall sustainability.

(I 2.4) Cost for system integration, (S_i 2.4.4) Easy to be integrated in local/regional grids

The assessment on the sustainability performances for the indicator "Cost for System Integration, Easy to be Integrated in Local/Regional Grids" examines how easily and cost-effectively different energy sources can be incorporated into local and regional electricity grids. This integration considers factors such as the need for additional infrastructure, compatibility with existing grid systems, and the ability to provide reliable and consistent power within a specific geographic area. The possible scores range from 1 to 5, with higher scores indicating *easier and less costly integration*. The results are presented in Fig. 4.2.9.

The assessment reveals that natural gas scores the highest at 3.97, indicating that it is the easiest and most cost-effective to integrate into local and regional grids. Nuclear power follows with a score of 3.73, demonstrating good integration capabilities despite higher costs. Hydropower scores 3.42, showing moderate ease of integration with some associated costs and environmental considerations. Intermittent renewables score the lowest at 2.70, highlighting significant challenges and higher costs related to their variable output and the need for additional infrastructure.

- Natural gas (score: 3.97/5) scores the highest at 3.97, reflecting its relative ease of integration into local and regional grids with moderate costs. Natural gas power plants can be deployed in various sizes, allowing for flexibility in matching local power demands. Their ability to provide quick and adjustable output makes them well-suited for supporting grid stability and accommodating varying loads within regional grids. The score of 3.97 indicates that natural gas is highly effective for integration into local and regional grids. Its flexibility in operation and the ability to scale capacity to meet demand make it a practical choice for many regions. However, while natural gas provides valuable operational flexibility, its reliance on fossil fuels and associated emissions are considerations for long-term sustainability.

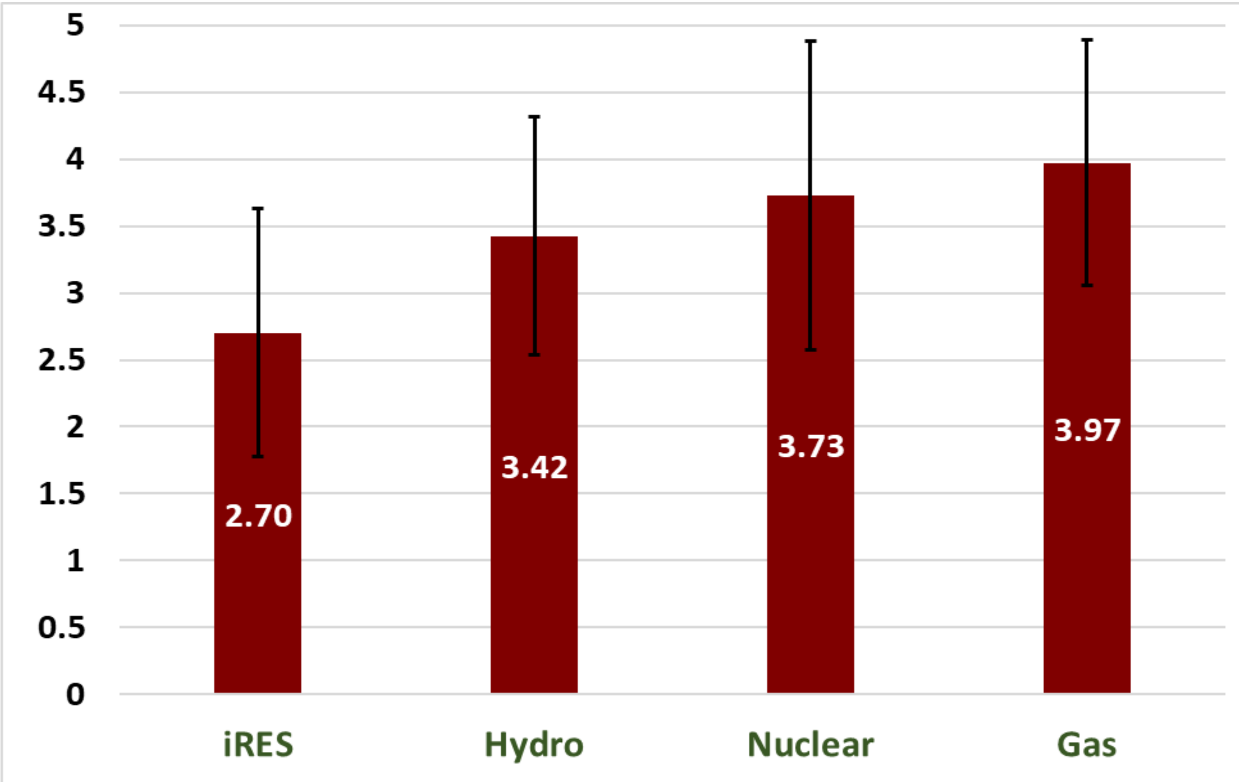


Fig. 4.2.9 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 2.4) Cost for system integration, (S_i 2.4.4) Easy to be integrated in local/regional grids

- Nuclear power (score: 3.73/5) scores 3.73, demonstrating a good level of ease for integration into local and regional grids, though with higher costs compared to natural gas. Nuclear plants provide a stable base load of power, which can be beneficial for grid stability. However, their large scale and high capital costs can make them more challenging to integrate, particularly in smaller or less developed grids. The score reflects that nuclear power is relatively easy to integrate into local and regional grids due to its consistent and reliable output. Despite its high initial investment and long lead times, once operational, nuclear power provides a steady supply that supports grid stability. The integration costs are manageable, but the scale and complexity of nuclear facilities may limit their deployment in smaller or less developed areas. New nuclear systems, such as SMRs, may reduce these difficulties in the medium-future.
- Hydropower (score: 3.42/5) scores 3.42, indicating moderate ease of integration with local and regional grids. Hydropower can be integrated effectively, particularly in areas with suitable water resources. Its ability to provide both base load and peak power can support grid stability. However, the integration costs and potential environmental impacts of constructing dams can be significant, particularly in regions where water resources are limited or where large-scale infrastructure is required. The score suggests that hydropower is reasonably easy to integrate into local and regional grids, especially where water resources are abundant. Its ability to provide a stable and adjustable power supply makes it a valuable component of grid infrastructure. However, the potential for high upfront costs and environmental considerations associated with dam construction can impact overall integration feasibility.

- Intermittent renewables (score: 2.70/5) score the lowest at 2.70, reflecting challenges in integration into local and regional grids with higher costs. Their variable output can make it difficult to match supply with demand consistently, requiring additional infrastructure such as energy storage or backup power sources to ensure reliability. This variability and the need for complementary systems increase the overall costs of integrating intermittent renewables into existing grid systems. The low score of 2.70 indicates that intermittent renewables face significant challenges in terms of integration into local and regional grids. Their variability necessitates additional investments in storage solutions or flexible backup power, which can increase integration costs. While renewable energy is crucial for reducing carbon emissions, the complexity of integrating these sources requires careful planning and investment in supporting technologies to ensure reliable and stable grid operation.

These results suggest the importance of considering integration ease and costs when evaluating energy sources for local and regional grids. Natural gas offers the most practical solution for flexible and cost-effective integration, while nuclear power and hydropower provide stable power with moderate integration challenges. Intermittent renewables, though environmentally beneficial, require additional infrastructure and planning to address their variability and ensure effective grid integration.

(I 2.4) Cost for system integration, (S_i 2.4.5) Realistic solution for large scale storage

The fast expansion of intermittent renewable energy generation, particularly wind and solar, in many regions of the world has created a significant incentive to build large-scale energy storage for electricity. Due to the growing annual share (desired or imposed) of electricity from renewable technologies having naturally-fluctuating power flows (like solar PV and wind) and relatively low load factors, the combined installed capacities of those technologies are expected to become much larger than conventional electrical peak power demand. The ability of such intermittent renewable sources to replace dispatchable sources, taking surplus power sometimes, and bridging intermittent gaps will depend on how much electricity storage can be produced. There are questions of scale – power and energy capacity. To evaluate different electrical storage systems in a range of applications and services, both value and cost must be accurately determined.

The assessment on the sustainability performances for this indicator examines how different energy sources support or require large-scale energy storage solutions, and the associated costs. Large-scale storage is crucial for balancing supply and demand, especially when integrating variable energy sources into the grid. The possible scores range from 1 to 5, with higher scores indicating *better integration with large-scale storage solutions and lower associated costs*. The results are presented in Fig. 4.2.10.

The assessment reveals that nuclear power scores the highest at 3.86, indicating good integration with large-scale storage solutions, though it does not heavily depend on them. Hydropower follows with a score of 3.56, benefiting from its ability to provide pumped storage and effectively manage energy fluctuations. Natural gas scores 3.39, reflecting moderate compatibility with storage solutions, primarily in its role as a flexible backup power source. Intermittent renewables score the lowest at 2.95, highlighting the significant challenges and higher costs associated with integrating these sources with large-scale storage due to their variability.

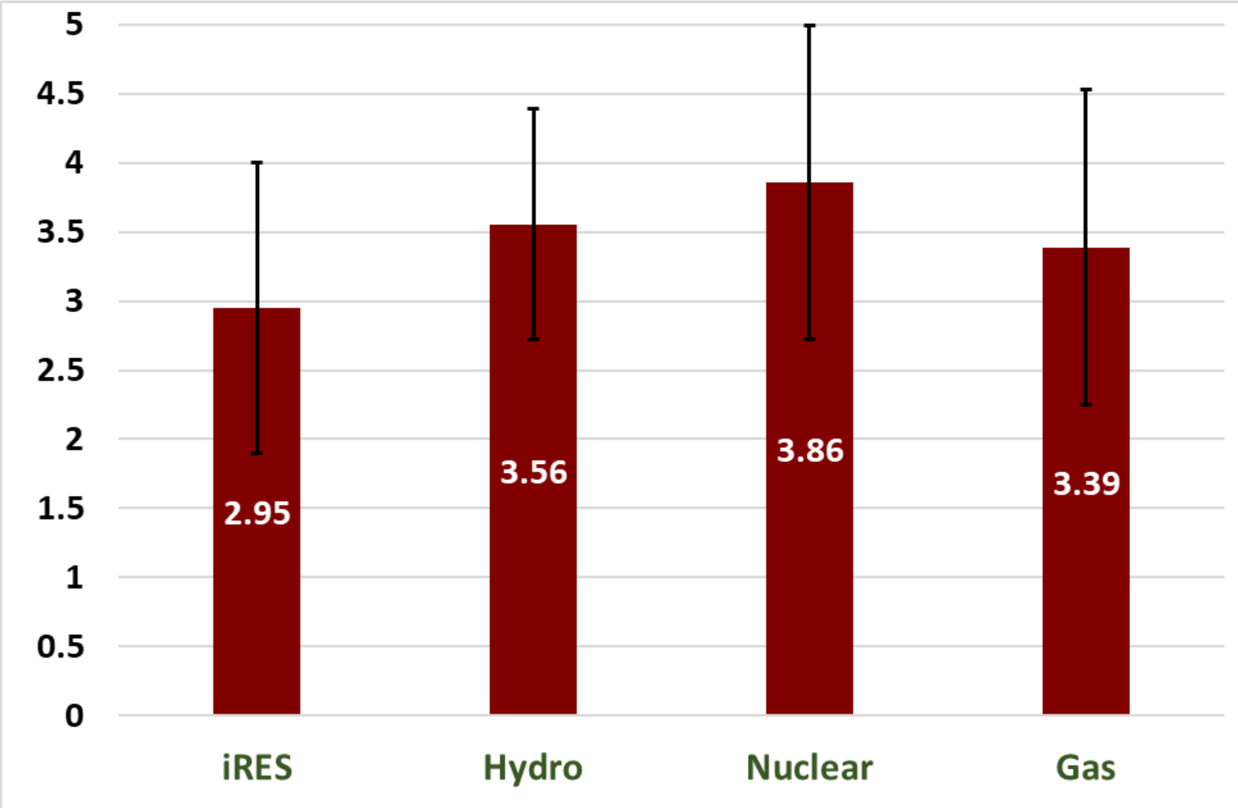


Fig. 4.2.10 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator I 2.4) Cost for system integration, (S_i 2.4.5) Realistic solution for large scale storage

- Nuclear power (score: 3.86/5) scores the highest at 3.86, reflecting its relatively strong compatibility with large-scale storage solutions. While nuclear power plants provide a consistent base load and do not inherently require significant storage capacity, the integration of nuclear power can be complemented by storage solutions to manage grid fluctuations and ensure stability. Nuclear power's steady output reduces the need for extensive storage compared to more variable sources. The thermal storage of energy is well developed (and simple, based on sand or rocks as suitable materials) and does not introduce critical challenges and risks. The higher score suggests that while nuclear power benefits from storage to enhance grid stability and flexibility, the overall cost and need for large-scale storage are lower compared to more variable energy sources. This makes nuclear power a practical option for grids where storage is a consideration.
- Hydropower (score: 3.56/5) scores 3.56, reflecting its good compatibility with large-scale storage solutions. Hydropower, especially in the form of pumped storage, can effectively serve as a large-scale storage method itself. Pumped storage facilities can store excess energy by pumping water to a higher elevation and then release it when needed to generate electricity. The effectivity is dependent on the difference in the elevation of the two reservoirs. The score indicates that hydropower is a strong candidate for integration with large-scale storage solutions. Its pumped storage capability provides a direct method of storing excess energy, making it a valuable component in managing grid stability. However, the construction and environmental impacts of such facilities can be significant, which should be considered when evaluating overall integration costs.

- Natural gas (score: 3.39/5) scores 3.39, showing moderate compatibility with large-scale storage solutions. While natural gas plants themselves do not directly involve large-scale storage, they can complement storage solutions by providing flexible, on-demand power to balance the variability of renewable sources. The integration of natural gas with storage systems can help manage grid stability but involves moderate costs for storage infrastructure. The score of 3.39 suggests that natural gas has a reasonable but not exceptional fit with large-scale storage solutions. Its role in providing flexible power helps to integrate storage systems more effectively, though it does not directly address the need for storage itself. The moderate score reflects the balance between the need for storage and the ability of natural gas to work alongside such solutions to stabilize the grid.

- Intermittent renewables (score: 2.95/5) score the lowest at 2.95, indicating the highest reliance on large-scale storage solutions. These energy sources are variable and do not produce a consistent output, necessitating significant storage capacity to manage supply and demand effectively. The costs associated with large-scale storage for intermittent renewables can be substantial due to the need for advanced storage technologies and infrastructure to handle their variability. The low score reflects the challenges and higher costs associated with integrating intermittent renewables with large-scale storage solutions. The variability of these sources requires substantial investment in storage technologies to ensure reliable grid operation. While intermittent renewables are critical for reducing carbon emissions, their integration into the grid is complex and costly, highlighting the need for ongoing innovation in storage solutions and grid management.

These results illustrate the varying degrees to which different energy sources interact with large-scale storage solutions. Nuclear power and hydropower offer more straightforward integration, with hydropower providing direct storage capabilities. Natural gas can complement storage systems, while intermittent renewables face the most substantial challenges in this area, requiring considerable investment in storage to ensure stable and reliable grid operation.

(I 2.5) External costs

External costs are those incurred regarding health and the environment, are quantifiable, but are not included into the cost of power and hence must be borne by society. They are especially concerned with the consequences of air pollution on human health, crop yields, and structures, as well as occupational sickness and accidents. The impact of global warming is now widely acknowledged. External expenses should be considered and, if feasible, quantified to help with cost-benefit analysis, technology comparison, and life cycle analysis.

The assessment on the sustainability performances for this indicator examines the costs that are not directly reflected in the market price of energy but are incurred by society and the environment. These external costs include factors such as health impacts, environmental degradation, and social consequences that result from the production and use of energy. The possible scores range from 1 to 5, with higher scores indicating *lower external costs* and thus better sustainability. The results are presented in Fig. 4.2.11.

The assessment reveals that intermittent renewables score the highest at 3.90, indicating the lowest external costs due to their minimal emissions and reduced environmental impact. Nuclear power follows with a score of 3.63, reflecting moderate external costs related to radioactive waste and safety concerns. Hydropower scores 3.56, showing moderate external costs associated with environmental and social impacts of dam construction. Natural gas scores the lowest at 2.41, highlighting the highest external costs due to emissions and methane leaks.

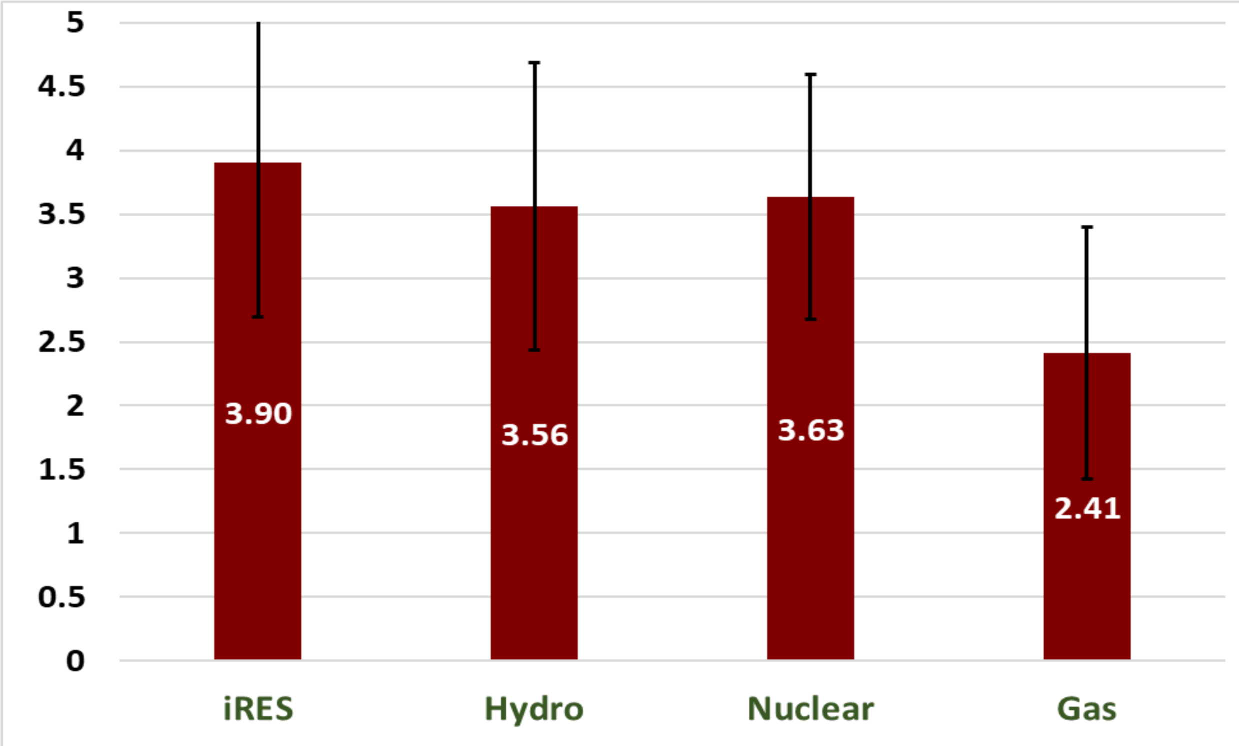


Fig. 4.2.11 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 2.5) External costs

- Intermittent renewables (score: 3.90/5) score the highest at 3.90, reflecting relatively low external costs. These energy sources have minimal direct emissions and generally cause less environmental and health damage compared to fossil fuels and nuclear energy. They do not involve combustion, which reduces air and water pollution, and their use typically leads to lower health impacts and less environmental degradation. The high score indicates that intermittent renewables have the lowest external costs among the considered energy sources. Their minimal emissions and reduced environmental impact contribute to a more sustainable energy profile. However, it is important to consider that while intermittent renewables have low external costs in terms of emissions and pollution, the impacts associated with the lifecycle of these technologies, such as resource extraction and waste management, are still relevant. Nonetheless, they remain the most environmentally friendly option in terms of external costs.

- Nuclear power (score: 3.63/5) scores 3.63, suggesting relatively moderate external costs. Nuclear energy has low direct emissions but presents significant challenges related to radioactive waste, potential accidents, and long-term waste management. The risks and costs associated with radioactive waste disposal and potential accidents contribute to the external costs of nuclear power. Although operational emissions are low, the potential for severe long-term impacts from radioactive waste and the need for stringent safety measures affect its overall sustainability. These factors must be carefully managed to mitigate their external costs and improve the sustainability profile of nuclear power.

- Hydropower (score: 3.56/5) scores 3.56, indicating moderate external costs. While hydropower generates electricity with no direct emissions, it can have significant environmental and social impacts. These include habitat disruption, changes to local ecosystems, and potential displacement of communities due to dam construction. The external costs associated with these factors contribute to the moderate score. The construction of dams and reservoirs can lead to environmental degradation and displacement issues. Despite its low emissions during operation, these external factors must be managed to improve the overall sustainability of hydropower projects.

- Natural gas (score: 2.41/5) scores the lowest at 2.41, reflecting the highest external costs among the considered energy sources. While natural gas burns cleaner than coal or oil, it still produces greenhouse gases and other pollutants, and methane leaks during extraction and transportation further contribute to environmental damage. The external costs related to air pollution, greenhouse gas emissions, and methane emissions are significant. Despite being cleaner than other fossil fuels, natural gas still has notable environmental and health impacts that contribute to its high external costs. These impacts highlight the need for greater consideration of alternative energy sources with lower external costs to improve overall sustainability.

Intermittent renewables offer the most favorable profile in terms of external costs, while nuclear power and hydropower present moderate external costs that need to be managed. Natural gas, despite being a cleaner fossil fuel, has the highest external costs and poses significant environmental and health challenges.

(I 2.6) Levelized cost of electricity (LCOE)

Levelized cost of electricity (LCOE) is the costs per unit of electricity generated, defined as the ratio of total lifetime expenses and the total expected output, expressed in terms of present value equivalent.

LCOE can be also expressed as the average price that would have to be paid by consumers for electricity delivered at the plant ″gate″ to repay exactly all costs incurred by the owner/operator of a plant, at the selected discount rate, in a defined time frame (lifetime of the plant) and without profits. Plant-level costs imply that for the LCOE calculation the overall system effects are not considered, i.e. the impact of a power plant on the electricity system.

The assessment on the sustainability performances for this indicator examines the average cost of generating electricity over the lifetime of a power plant, expressed per unit of electricity produced. LCOE encompasses all costs associated with energy production, including capital costs, operation and maintenance costs, and fuel costs, normalized over the total electricity output. The possible scores range from 1 to 5, with higher scores indicating *lower LCOE and better economic competitiveness*. The results are presented in Fig. 4.2.12.

The assessment reveals that nuclear power scores the highest at 3.60, indicating a competitive LCOE due to low operational and fuel costs. Hydropower follows closely with a score of 3.58, benefiting from low ongoing costs despite high initial capital requirements. Natural gas scores 3.15, reflecting moderate LCOE with lower capital costs but higher fuel expenses. Intermittent renewables score the lowest at 3.08, showing the highest LCOE due to the need for additional infrastructure to manage variability and integrate with the grid.

- Nuclear power (score: 3.60/5) scores the highest at 3.60, reflecting a relatively competitive LCOE. However, note that this is a dissensual result (longer error bar), possibly reflecting differential knowledge of this economic concept. While the capital costs for building nuclear power plants are high, the operational and fuel costs are relatively low. Once operational, nuclear plants provide a stable and substantial amount of electricity at a relatively low marginal cost. This leads to a favorable LCOE over the long term. The long-term cost-effectiveness of nuclear energy is reflected in this score, making it an economically viable option for large-scale, continuous power generation.

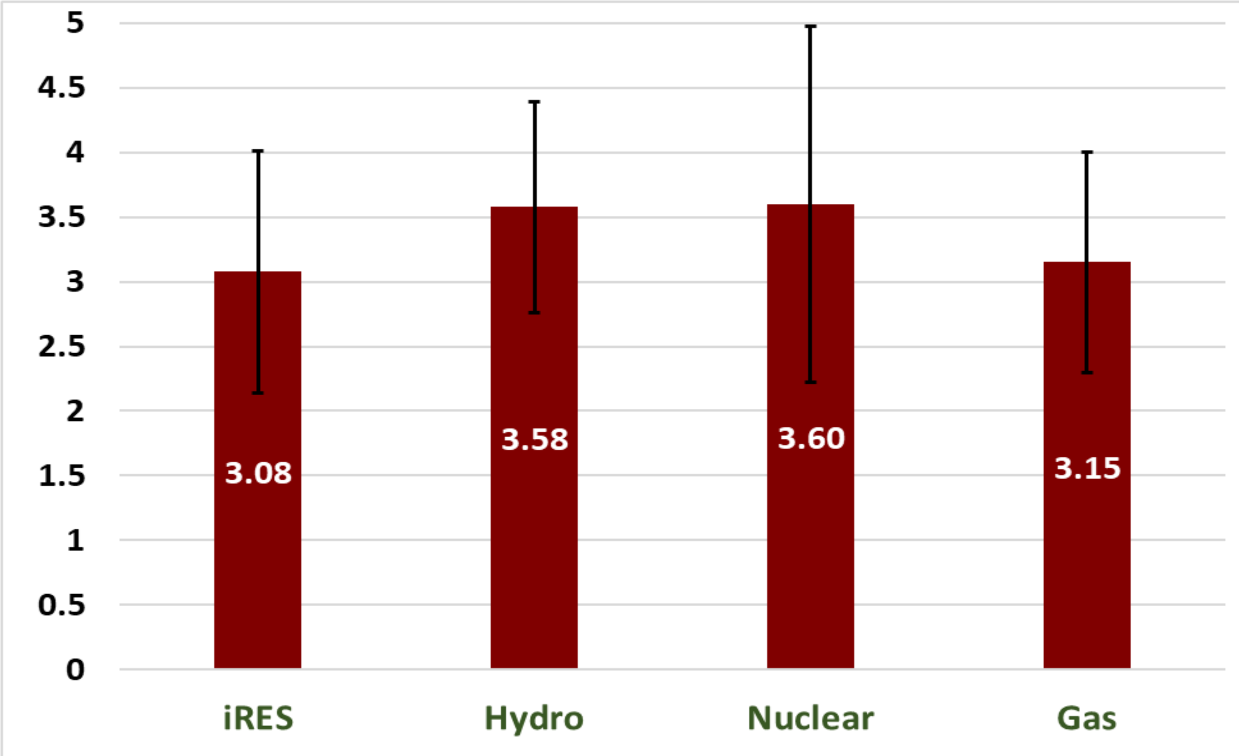


Fig. 4.2.12 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 2.6) LCOE

- Hydropower (score: 3.58/5) scores 3.58, showing a competitive LCOE. Hydropower plants generally have high capital costs due to the infrastructure required for dams and turbines, but their operational and maintenance costs are low. Hydropower also benefits from a long operational life and low fuel costs (water). Although initial construction costs can be significant, the overall cost of producing electricity from hydropower remains competitive over the plant's lifetime.
- Natural gas (score: 3.15/5) scores 3.15, reflecting a moderate LCOE. Natural gas plants typically have lower capital costs compared to nuclear and hydropower plants. However, the fuel costs and operational expenses can be higher due to the need for continuous fuel supply. Despite these factors, natural gas remains relatively cost-effective for electricity generation. The score of 3.15 suggests that natural gas has a moderate LCOE, benefiting from lower capital costs but facing higher fuel and operational expenses. This score reflects the trade-off between capital and fuel costs in determining the overall economic competitiveness of natural gas as an electricity source.
- Intermittent renewables (score: 3.08/5) score the lowest at 3.08. The capital costs for renewable energy technologies have decreased significantly, but these sources still face challenges related to variability and intermittency, which can require additional investment in storage or backup systems. The LCOE for intermittent renewables can vary depending on location and resource availability, but it is generally higher than that of more established sources due to these additional integration costs. The score indicates that intermittent renewables have the highest LCOE among the considered energy sources. While the decreasing capital costs for renewable technologies are a positive factor, the need for additional storage and grid management to address variability impacts overall cost competitiveness. This highlights the ongoing challenges in reducing LCOE for renewables despite advances in technology.

These results emphasize the economic aspects of different energy sources in terms of LCOE. Nuclear power and hydropower offer favorable long-term costs, while natural gas provides moderate cost-effectiveness. Intermittent renewables face higher LCOE due to the additional costs of integration and variability management, though technological advancements and cost reductions may help improve their competitiveness in the future.

(I 2.7) Macro-economic impact

Macro-economic impact refers to the overall effects that energy technologies have on a national or the global economy. Generally, the development of new energy technologies may stimulate the economic growth, investment, infrastructure development, job creation, etc. By reducing the dependence on fossil fuel and on the imported resources, a reduction of the economic vulnerabilities may occur. A clean energy can produce economic benefits in terms of avoided healthcare costs, increased agricultural productivity, and reduced damage from extreme weather events. Energy technologies with reduced cost of energy can lower energy bills for households and businesses creating opportunities to buy other goods and services, boosting overall economic activity. The development and deployment of new energy technologies often require substantial investment in research, development, and infrastructure.

The assessment on the sustainability performances for this indicator examines the broader economic effects of different energy sources on the economy at large. This includes factors such as job creation, economic growth, energy security, and the impact on local and national economies. The possible scores range from 1 to 5, with higher scores indicating *more favorable macro-economic impacts*. The results are presented in Fig. 4.2.13.

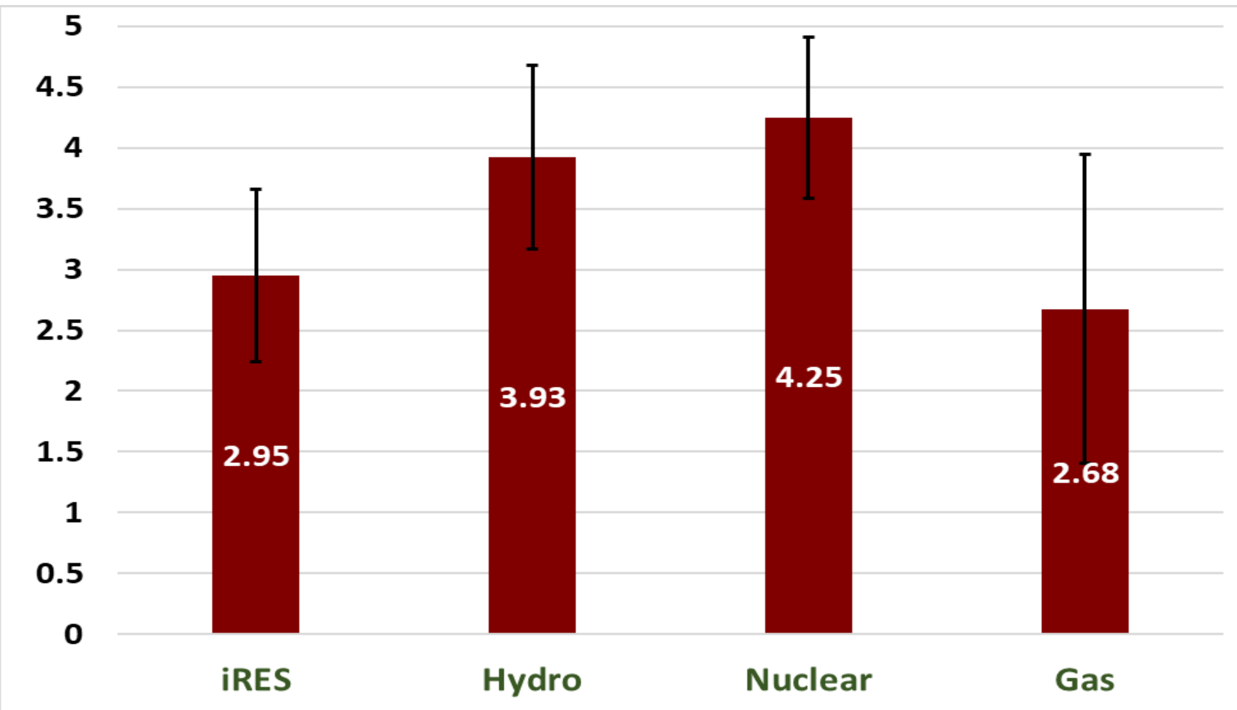


Fig. 4.2.13 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 2.7) Macro-economic impact

The assessment reveals that nuclear power scores the highest at 4.25, reflecting its significant positive macro-economic impact through job creation, technological advancement, and energy security. Hydropower follows with a score of 3.93, indicating a strong macro-economic impact due to infrastructure investment and regional development benefits. Natural gas scores 3.06, showing a moderate macro-economic impact with benefits that can be variable and dependent on market conditions. Intermittent renewables score the lowest at 2.95, highlighting a lower macro-economic impact due to integration challenges, variability issues, and relative low impact in job creation and local development.

- Nuclear power (score: 4.25/5) scores the highest at 4.25, reflecting its significant positive macro-economic impacts. Nuclear plants tend to provide high-paying, long-term jobs and contribute to energy security through stable, baseload power generation. Additionally, the long operational life and the need for skilled labor and services create substantial economic benefits. Nuclear energy can also reduce dependence on imported fuels, contributing to national energy security. The benefits include job creation, technological development, and reduced fuel import dependence, making nuclear power a strong contributor to economic stability and growth.
- Hydropower (score: 3.93/5) scores 3.93, reflecting its positive macro-economic impact. Hydropower projects often involve significant investment in infrastructure, which can stimulate local economies and create jobs during the construction phase. The operational phase also provides long-term employment and can contribute to regional development. Additionally, hydropower offers a stable and reliable energy source, supporting economic stability. The long-term operational stability of hydropower projects further supports economic growth and regional development.
- Natural gas (score: 3.06/5) scores 3.06, reflecting a moderate macro-economic impact (but note that this mean rating is dissensual, possibly translating different knowledge, interpretations or sensitivities) Natural gas projects can create jobs and stimulate economic activity, particularly in regions with significant natural gas reserves. However, the economic benefits can be more variable depending on market conditions and the volatility of fuel prices. Additionally, natural gas still involves fossil fuel extraction and may face long-term economic challenges related to environmental regulations and climate policies. While it can provide economic benefits through job creation and local investments, its overall impact is less favorable compared to nuclear and hydropower. The volatility of fuel prices and potential future regulations on fossil fuels may affect its long-term economic benefits.
- Intermittent renewables (score: 2.95/5) score the lowest at 2.95, indicating a lower macro-economic impact. While these technologies are growing and can create jobs in the renewable energy sector, their economic impact can be limited by factors such as lower energy density and variability, which can affect their integration into existing energy systems. Also the localization of jobs is quite limited, The need for additional infrastructure, such as energy storage and grid upgrades, can also impact their overall economic contribution. The low score of 2.95 indicates that intermittent renewables currently have the least favorable macro-economic impact among the considered energy sources. Although they contribute to job creation and technological advancement, their economic benefits are tempered by integration challenges and variability issues, which can limit their broader economic impact.

These results describe the broader economic considerations of different energy sources. Nuclear power and hydropower offer substantial economic benefits, while natural gas provides moderate benefits with potential challenges. Intermittent renewables face more challenges in delivering a significant macro-economic impact, although advancements in technology and infrastructure could improve their economic contribution over time.

(I 2.8) Applicability for cogeneration

Cogeneration means that a plant supplies both electricity and heat, thus increasing the efficiency from 30-33% (usually, for heat conversion to the electricity) to 75-90%. The concept is frequently used for conventional plants.

The mandatory condition to apply for cogeneration is that a technology to generate heat by burning a traditional fossil fuel or by fission reaction and also, nowadays, by concentrating the solar power (Concentrating Solar Power). As a result, only the Coal, Gas, Solar (CSP) and nuclear technologies are suitable for cogeneration, the rest ones, Wind, Solar (PV) and Hydro not being able to apply for cogeneration (N/A).

The assessment on the sustainability performances for this indicator examines how well different energy sources can be used for cogeneration, which involves simultaneously producing electricity and useful heat from the same energy source. Cogeneration, or combined heat and power (CHP), can enhance overall efficiency and reduce fuel consumption. The possible scores range from 1 to 5, with higher scores indicating *better applicability for cogeneration*. The results are presented in Fig. 4.2.14.

The assessment reveals that natural gas scores the highest at 4.33, indicating the best applicability for cogeneration due to its ability to efficiently provide both electricity and heat. Nuclear power follows with a score of 4.14, showing strong potential for cogeneration, although practical and economic considerations can limit its use. Intermittent renewables score the lowest at 1.92, reflecting poor applicability for cogeneration due to their intermittent nature and lack of heat production. Hydropower scores 1.17, indicating very limited applicability for cogeneration as it focuses solely on electricity generation.

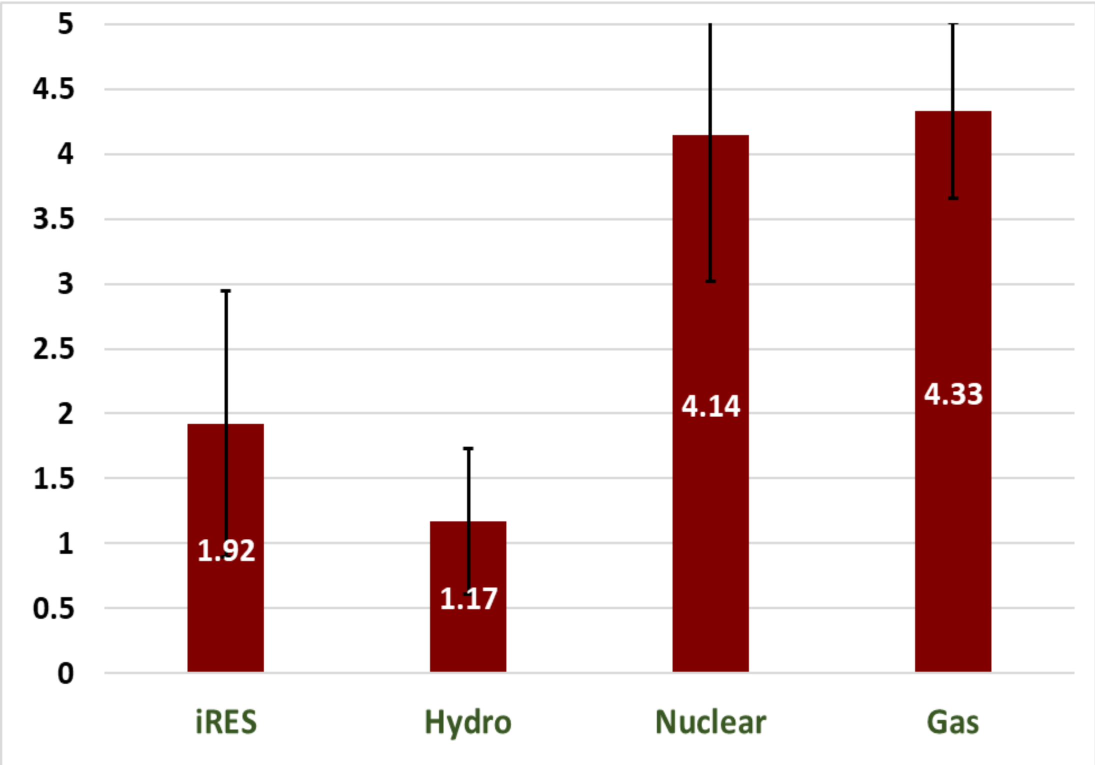


Fig. 4.2.14 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 2.8) Applicability for cogeneration

- Natural gas (score: 4.33/5) scores the highest at 4.33, reflecting its excellent applicability for cogeneration. Natural gas plants are highly versatile and can be efficiently used in cogeneration systems. They can provide both electricity and heat in a highly efficient manner, making them ideal for applications where both forms of energy are needed. Natural gas cogeneration systems are commonly used in industrial and district heating applications due to their flexibility and efficiency. Its ability to provide both electricity and heat efficiently makes it a strong candidate for applications requiring combined energy outputs. This high applicability contributes to its overall efficiency and effectiveness in energy systems.
- Nuclear power (score: 4.14/5) scores 4.14, indicating strong applicability for cogeneration. Nuclear reactors can be designed for cogeneration, particularly in combined heat and power (CHP) applications. The ability to produce high-temperature steam makes nuclear power suitable for cogeneration in industrial processes or district heating systems. However, the complexity and cost of adapting nuclear plants for cogeneration can be high. The score of 4.14 shows that nuclear power has a significant potential for cogeneration. While it offers high efficiency in producing both electricity and heat, the practical implementation and economic feasibility can be more complex compared to natural gas. Nonetheless, it remains a viable option for cogeneration, especially in large-scale applications.
- Intermittent renewables (score: 1.92/5) score the lowest at 1.92, reflecting poor applicability for cogeneration. These energy sources are typically not suited for cogeneration because they generate electricity intermittently and do not produce heat in a manner that can be efficiently utilized for combined heat and power. The variability in generation makes it challenging to integrate cogeneration with intermittent renewables. Their inability to provide consistent and controllable heat alongside electricity makes them less suitable for cogeneration applications. The focus for intermittent renewables is generally on electricity production alone, without integration for combined heat and power.
- Hydropower (score: 1.17/5) scores 1.17, reflecting very low applicability for cogeneration. While hydropower generates directly the electricity, it does not inherently produce heat in a way that can be used for cogeneration. The design and operational characteristics of hydropower plants are not conducive to producing both electricity and heat effectively. The nature of hydropower systems focuses on electricity generation from flowing water, and they do not provide the heat necessary for cogeneration processes. Thus, hydropower is not typically used in cogeneration setups.

These results suggest that natural gas and nuclear power are the most suitable energy sources for cogeneration applications, offering significant benefits in terms of efficiency and effectiveness. In contrast, intermittent renewables and hydropower are less compatible with cogeneration due to their operational characteristics and focus on electricity generation.

(I 2.9) Level of standards generated, rules and control (S_i 2.9.1) Maturity of the authorization process

The authorization process for any type of plant producing energy is laborious, but there are differences between technologies and countries.

The assessment on the sustainability performances for this indicator examines how well-established and effective the regulatory frameworks and authorization processes are for different energy sources. This includes the clarity and rigor of standards, the maturity of regulatory procedures, and the overall effectiveness of control mechanisms. The possible scores range from 1 to 5, with higher scores indicating a *more mature and well-regulated authorization process*. The results are presented in Fig. 4.2.15.

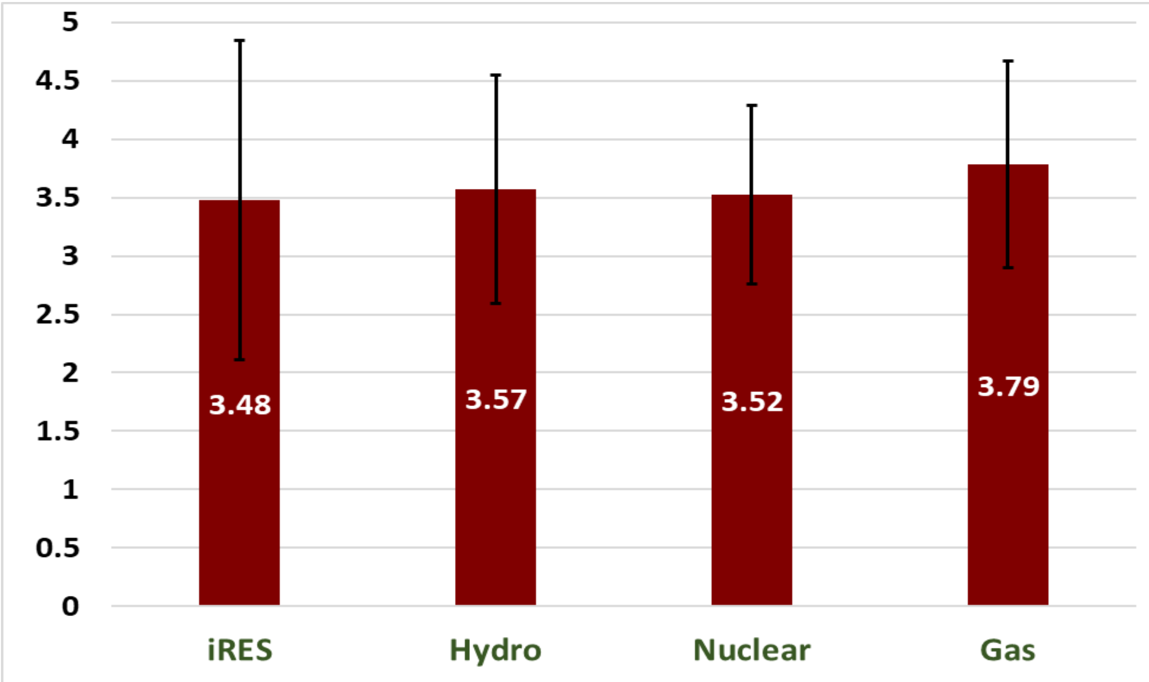


Fig. 4.2.15 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 2.9) Level of standards generated, rules and control (S_i 2.9.1) Maturity of the authorization process

The assessment reveals that natural gas scores the highest at 3.79, indicating a mature and well-established authorization process with robust standards and controls. Hydropower follows with a score of 3.57, reflecting a strong regulatory framework but with complexities related to large-scale projects. Nuclear power scores 3.52, showing a high level of regulatory maturity and stringent safety measures, albeit with a more complex authorization process. Intermittent renewables score 3.48, indicating a developing but increasingly mature authorization process as regulations and standards continue to evolve.

- Natural gas (score: 3.79/5) scores the highest at 3.79, reflecting a relatively mature and well-established authorization process. The natural gas industry benefits from a long history of regulatory development and standardization, with well-defined procedures for exploration, extraction, transportation, and combustion. Regulatory frameworks for natural gas are generally comprehensive and have evolved to address environmental and safety concerns effectively. The industry has established robust standards and regulations over time, contributing to effective oversight and control. This mature framework helps ensure safety, environmental protection, and operational efficiency, making natural gas a well-regulated sector.

- Hydropower (score: 3.57/5) scores 3.57, reflecting a strong level of standards and control, though slightly less mature compared to natural gas. The regulatory processes for hydropower involve comprehensive environmental impact assessments, safety regulations, and standards for dam construction and operation. However, the complexity of hydropower projects, particularly large-scale ones, can lead to longer and more complex authorization processes. The score indicates that hydropower has a well-developed authorization process with solid standards and controls.

- Nuclear power (score: 3.52/5) scores 3.52, indicating a mature but highly regulated authorization process. Nuclear energy requires stringent safety standards, detailed regulatory frameworks, and rigorous authorization procedures due to the potential risks associated with radioactive materials and plant operations. The high level of scrutiny and control ensures safety but can also result in a more complex and lengthy authorization process. The complexity of nuclear regulations reflects the need for rigorous safety measures and thorough oversight. While this ensures high safety levels, it can also make the authorization process more challenging and time-consuming.
- Intermittent renewables (score: 3.48/5) score 3.48, reflecting a relatively mature but less standardized authorization process compared to natural gas and nuclear power. Note however the relatively dissensual character of the rating, which may translate differential awareness, knowledge or interpretation of these processes. The regulatory frameworks for intermittent renewables are evolving as the technology and deployment scale increase. Standards and rules are being developed to address specific issues related to integration, grid connection, and environmental impact. While the regulatory frameworks are maturing, they are still catching up with the rapid advancements and scaling of renewable technologies. This evolving nature of the authorization process reflects ongoing efforts to enhance regulations and standards for renewables.

These results highlight that while all energy sources have established standards and controls, natural gas and hydropower have more mature and well-defined authorization processes. Nuclear power has a highly regulated framework that ensures safety but can complicate the authorization process. Intermittent renewables are progressing towards a more mature authorization process as the industry and regulations contiue to develop.

(I 2.9) Level of standards generated, rules and control (S_i 2.9.2) Level of industrial codes and standards

Level of Industrial Codes and Standards as a sustainability indicator refers to the comprehensiveness, rigor, and effectiveness of the regulatory frameworks, codes, and standards that govern the design, construction, operation, and maintenance of technologies or infrastructure within a specific sector. This indicator assesses how well these codes and standards contribute to the overall sustainability of the sector by ensuring safety, reliability, environmental protection, and efficiency.

The assessment on the sustainability performances for this indicator examines the robustness and maturity of the industrial codes and standards applied to different energy sources. This includes how well-developed and comprehensive the industry guidelines, safety protocols, and operational standards are for each energy source. Higher scores indicate *more developed and rigorous standards and codes*. The results are presented in Fig. 4.2.16.

The assessment shows that natural gas scores the highest at 4.44, indicating the most mature and comprehensive set of industrial codes and standards. Nuclear power follows with a score of 3.51, reflecting strong but somewhat variable standards. Hydropower scores 3.34, showing solid standards with some variability due to project complexity. Intermittent renewables score the lowest at 2.95, reflecting a less developed set of standards that are evolving as the technology progresses.

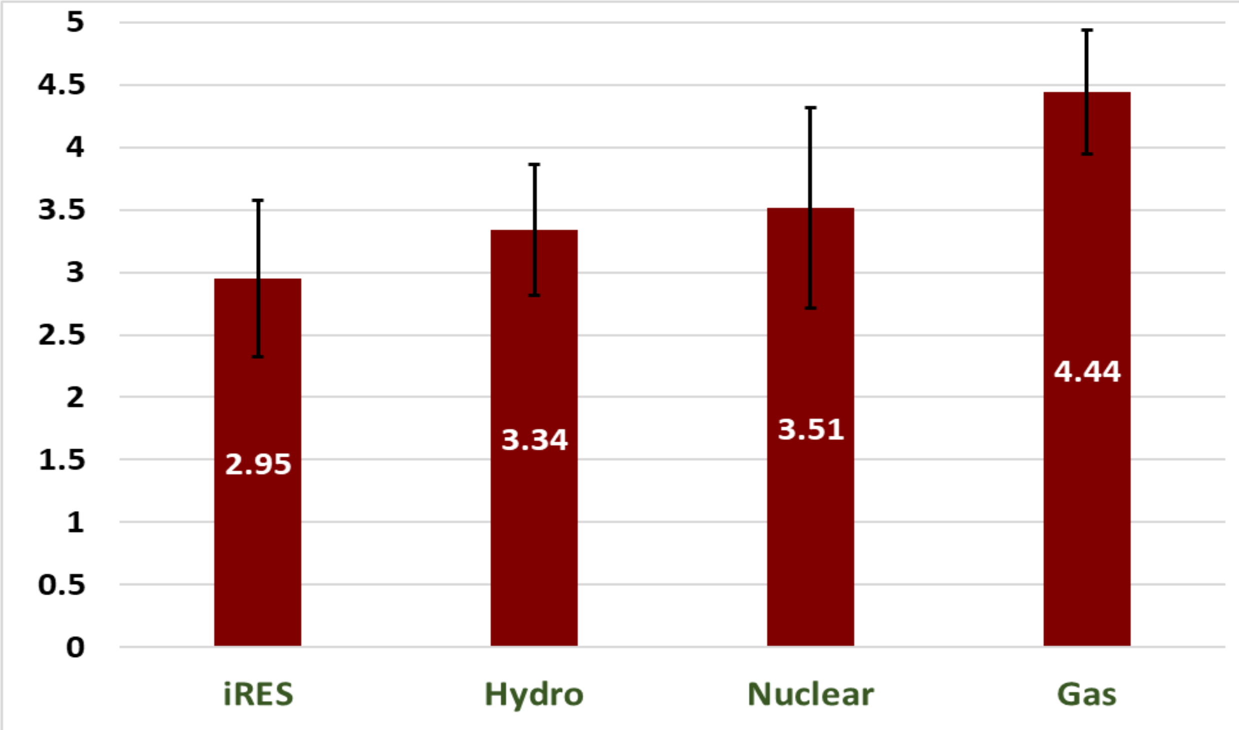


Fig. 4.2.16 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 2.9) Level of standards generated, rules and control (S_i 2.9.2) Level of industrial codes and standards

- Natural gas (score: 4.44/5) scores the highest at 4.44, reflecting a very mature and well-established set of industrial codes and standards. The natural gas industry has long been regulated with detailed standards covering exploration, extraction, processing, transportation, and distribution. The regulatory frameworks for natural gas are extensive and continuously updated to address safety, environmental impact, and operational efficiency. This maturity reflects the long history of natural gas use and the extensive regulatory frameworks that ensure safety and efficiency across its entire supply chain. The industry's standards are well-established and continually refined to adapt to new challenges and technologies.

- Nuclear power (score: 3.51/5) scores 3.51, indicating a strong but, in the opinion of respondents, somewhat less developed set of industrial codes and standards compared to natural gas. The nuclear industry has stringent safety regulations and operational standards due to the high risks associated with radioactive materials and nuclear reactions. These standards cover design, operation, safety, and waste management, though the regulatory frameworks can vary by country. The standards are comprehensive and address critical safety and operational aspects, but the variation in regulatory approaches across different regions can impact overall consistency. Nevertheless, the nuclear industry's standards are crucial for ensuring safety and managing risks associated with nuclear energy.

- Hydropower (score: 3.34/5) scores 3.34, reflecting a well-established but slightly less comprehensive set of industrial codes and standards compared to nuclear and natural gas. Hydropower standards cover aspects like dam safety, environmental impact, and operational efficiency. However, the complexity of large-scale hydropower projects and the diverse range of environmental considerations can impact the uniformity of these standards. The score of 3.34 indicates that while hydropower has a good set of industrial codes and standards, there is variability in the comprehensiveness and implementation of these standards. The industry's standards are solid but may not be as extensively developed or uniformly applied as those for natural gas and nuclear power. The complexity of hydropower projects can lead to variations in regulatory practices.

- Intermittent renewables (score: 2.95/5) score the lowest at 2.95, indicating a less developed set of industrial codes and standards. The rapid advancement of renewable technologies and their integration into the grid has led to evolving standards, but these are still catching up with the more mature sectors. Standards for intermittent renewables cover technology performance, safety, and integration but may not be as comprehensive or uniformly applied. The low score of 2.95 reflects that intermittent renewables are in a phase of development with standards that are evolving but not yet as mature as those for natural gas, nuclear, and hydropower. The industry is actively working to develop and refine standards to address new technologies and integration challenges, but it has not yet reached the level of robustness seen in more established sectors.

These results highlight that while natural gas has the most developed industrial codes and standards, the nuclear and hydropower industries also have robust frameworks but with varying levels of comprehensiveness. The intermittent renewables sector, being newer and rapidly evolving, is working towards more established standards as the technology and integration challenges continue to advance.

(I 2.9) Level of standards generated, rules and control (S_i 2.9.3) Needs for technical support

Strong technical support supposes a solid foundation in the basic concepts and tools that are relevant to a field of activity. Depending on the domain, this may include experimental infrastructures, hardware, software, networking, security, cloud, databases, web development, and more. There is no energy technology that does not need for technical support, this being required during the entire technology's lifetime, starting to the design stage, construction, commissioning, operation and decommissioning. The needs for technical support can be different, according to the stage and technology type.

The assessment on the sustainability performances for this indicator examines the extent to which different energy sectors require technical support to meet industry standards and regulatory requirements. This includes the need for expertise, guidance, and external assistance to ensure compliance with established rules and standards. Higher scores indicate *lower needs for technical support*, *reflecting greater self-sufficiency in meeting standards and controls*. The results are presented in Fig. 4.2.17.

The assessment reveals that natural gas scores the highest at 3.79, indicating the lowest need for external technical support, reflecting a mature and self-sufficient industry. Hydropower follows with a score of 3.21, showing a moderate need for technical support due to project complexity and environmental considerations. Intermittent renewables score 2.71, indicating a higher need for technical support due to evolving technologies and integration challenges. Nuclear power scores the lowest at 2.55, reflecting the highest need for specialized technical support due to the complexity and stringency of its regulatory requirements.

- Natural gas (score: 3.79/5) scores the highest at 3.79, indicating that this sector has a relatively low need for additional technical support to meet standards and regulatory requirements. The natural gas industry benefits from established technologies, robust frameworks, and a long history of development, which means it often operates with well-developed internal expertise and processes. The high score of 3.79 suggests that the natural gas sector has a high degree of self-sufficiency and requires less external technical support compared to other sectors. The mature regulatory frameworks and established practices in natural gas contribute to its ability to meet standards with minimal additional support.

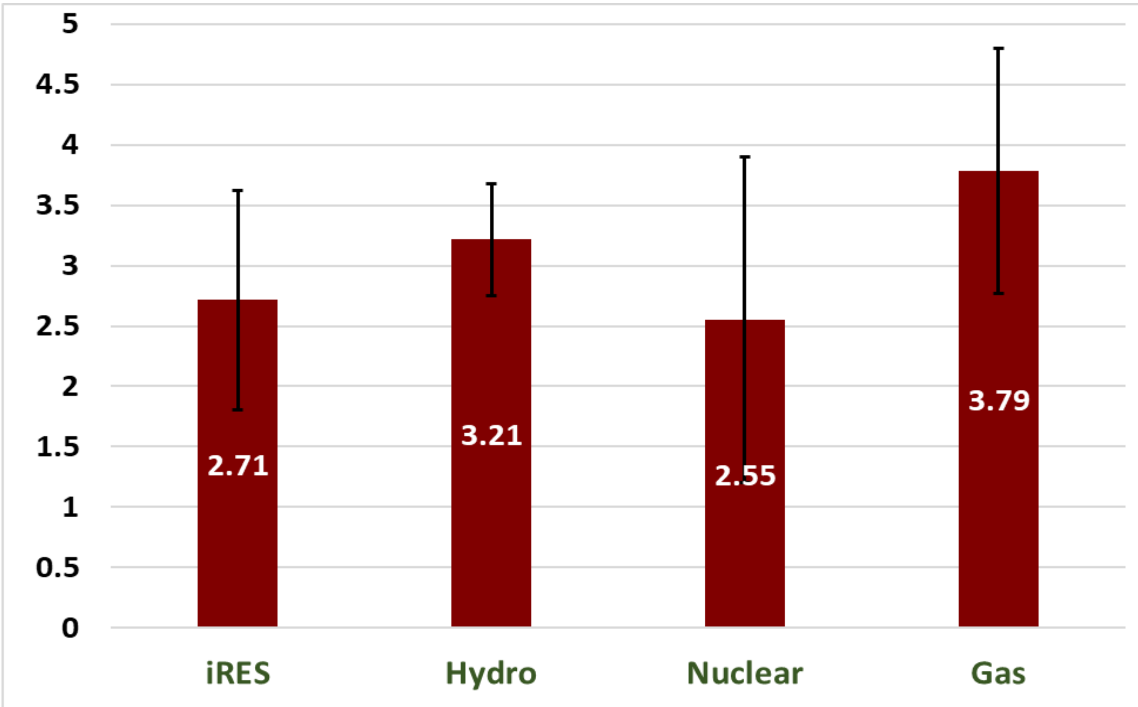


Fig. 4.2.17 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 2.9) Level of standards generated, rules and control (S_i 2.9.3) Needs for technical support

- Hydropower (score: 3.21/5) scores 3.21, reflecting a moderate need for technical support. While hydropower technology is well-established, the complexity of large-scale projects and the environmental considerations involved can create scenarios where additional technical support is beneficial. This support might include expertise in dam engineering, environmental impact assessments, and operational management. The score of 3.21 indicates that while hydropower is relatively self-sufficient, it still benefits from some level of technical support to address the specific needs of large-scale projects and environmental challenges. The sector's well-defined standards and practices are complemented by external expertise as needed.

- Intermittent renewables (score: 2.71/5) score the lowest at 2.71, indicating a higher need for technical support. This is due to the rapidly evolving technology, integration challenges with existing grids, and the ongoing development of standards. The sector often requires additional expertise for technology deployment, integration, and optimization. The low score of 2.71 reflects the significant need for technical support in the intermittent renewables sector. The rapid advancements and ongoing development in renewable technologies mean that external expertise and guidance are frequently needed to ensure successful implementation and compliance with emerging standards.

- Nuclear power (score: 2.55/5) scores 2.55, indicating the highest need for technical support among the considered sectors. This is also the most dissensual result, translating different views on needs for technical support. The nuclear industry involves complex technologies and stringent regulatory requirements related to safety, radioactive materials, and waste management. As a result, there is a high demand for specialized technical support to address these challenges. The score suggests that nuclear power requires significant external technical support to meet its rigorous standards and safety requirements. The complexity of nuclear technology and the critical nature of safety and compliance issues necessitate extensive expert involvement and support.

These results highlight that while natural gas and hydropower manage with relatively lower external support, intermittent renewables and nuclear power require more technical assistance to navigate their specific challenges and ensure compliance with standards.

4.2 Pillar 3, Social

(I 3.1) Jobs created (S_i 3.1.1) Direct high-education jobs

The assessment on the sustainability performances for this indicator examines the extent to which different energy sectors create employment opportunities for individuals with higher education qualifications. This indicator reflects the sector’s contribution to specialized job creation that requires advanced skills and education. Higher scores indicate a *greater creation of such high-education jobs, reflecting a sector's investment in skilled labor and expertise*. The results are presented in Fig. 4.3.1.

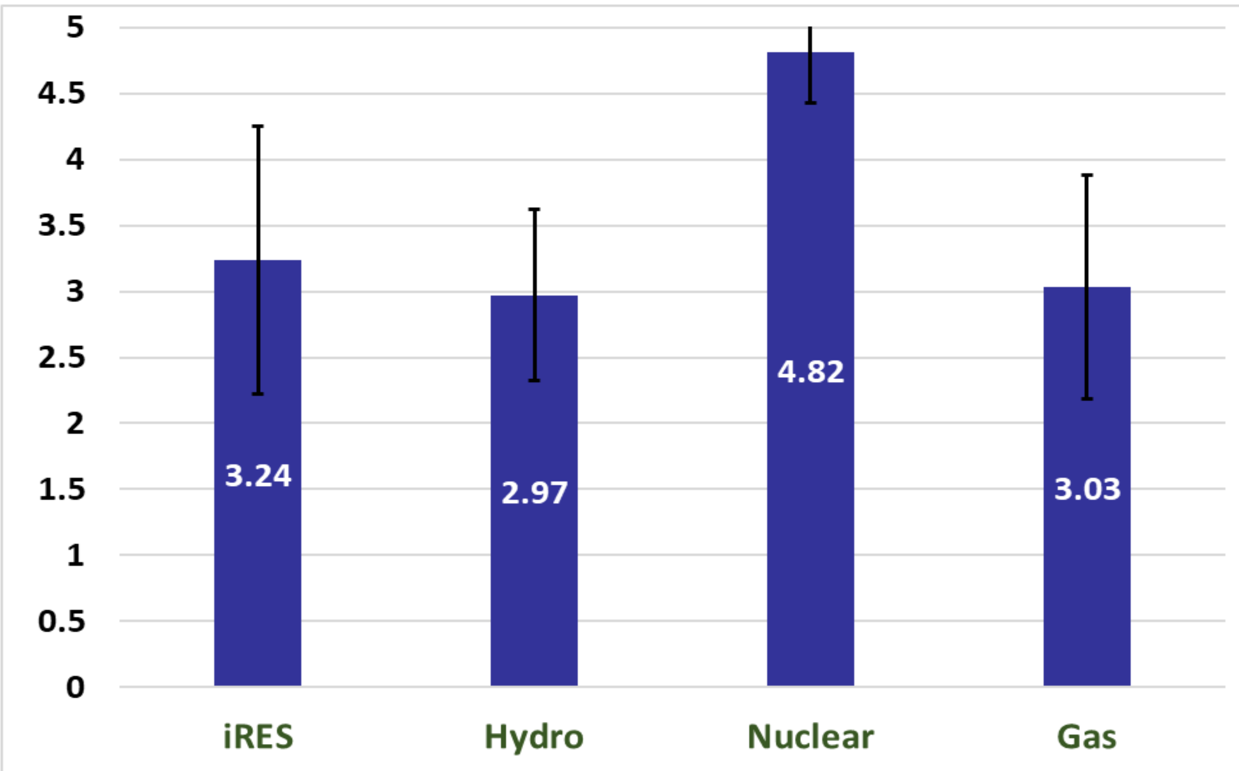


Fig. 4.3.1 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator I 3.1 Jobs created, sub-indicator 3.1.1 Direct high-education jobs

The assessment highlights that nuclear power scores the highest at 4.82, reflecting the creation of a significant number of high-education jobs due to the complex nature of the industry. Intermittent renewables follow with a score of 3.24, indicating a moderate level of high-education job creation. Natural gas scores 3.03, showing a fair amount of such jobs but with a broader range of roles. Hydropower scores the lowest at 2.97, suggesting that it creates fewer high-education jobs relative to the other sectors.

- Nuclear power (score: 4.82/5) scores the highest at 4.82, reflecting a significant creation of direct high-education jobs. The nuclear industry requires highly specialized knowledge and skills due to the complexity of nuclear technology, safety protocols, and regulatory requirements. This translates into a high demand for engineers, physicists, and other professionals with advanced degrees.

The exceptionally high score of 4.82 indicates that the nuclear power sector generates a substantial number of high-education jobs. This is due to the need for highly skilled professionals to operate and manage complex nuclear plants, as well as to conduct research and ensure safety and regulatory compliance. The sector's reliance on advanced technology and stringent safety standards contributes to its high score.

- Intermittent renewables (score: 3.24/5) score 3.24, indicating a moderate level of direct high-education job creation. The renewable energy sector does create high-education jobs, particularly in areas like engineering, research and development, and project management. However, the overall score reflects that the sector has a more varied job profile, including roles that do not always require advanced degrees. The score suggests that while intermittent renewables do contribute to high-education job creation, the proportion is not as high as in nuclear power. The sector is growing rapidly and does provide opportunities for advanced degree holders, but it also includes a broader range of roles that may not require as specialized educational backgrounds.
- Natural gas (score: 3.03/5) scores 3.03, reflecting a moderate level of high-education job creation. The natural gas industry does create specialized roles, particularly in engineering, geology, and environmental sciences. However, the sector's overall job profile includes a significant number of roles that do not necessarily require advanced education. The score indicates that the natural gas sector generates a fair number of high-education jobs, but not to the same extent as the nuclear industry. The presence of technical and professional roles in the sector contributes to this score, but the diversity of job types within natural gas, including those requiring less specialized education, affects the overall rating.
- Hydropower (score: 2.97/5) scores the lowest at 2.97, suggesting that it creates fewer direct high-education jobs compared to the other sectors. Although hydropower projects require engineering and technical expertise, the overall demand for high-education jobs in this sector is lower relative to the complexity and specialization needed in nuclear power and some renewable technologies. The score of 2.97 reflects that while hydropower does involve high-education roles, the number of such positions is less compared to the nuclear and renewable sectors. The hydropower industry employs engineers and other specialists, but the proportion of high-education jobs is lower, likely due to the more mature and standardized technology and processes in this sector.

These results show that the nuclear power sector stands out for its high demand for advanced expertise, while intermittent renewables and natural gas also contribute to high-education job creation but to a lesser extent. Hydropower creates the fewest high-education jobs, reflecting a lower overall requirement for advanced education in the sector.

(I 3.1) Jobs created (S_i 3.1.2) Jobs in contributing industries

The sustainability indicator "Jobs Created, Jobs in Contributing Industries" for energy technology comparison examines the employment impacts associated with the energy sector, specifically focusing on the jobs generated within industries that support and supply resources, services, and materials to the primary energy technology. This indicator is crucial for understanding how energy technologies influence broader economic activity beyond their direct implementation and operation.

The assessment on the sustainability performances for this indicator examines the extent to which different energy sectors contribute to employment in associated or supporting industries. This indicator reflects the broader economic impact of each energy sector by considering how it stimulates job creation in related sectors such as manufacturing, construction, and service industries. Higher scores indicate a *greater positive impact on employment in contributing industries*. The results are presented in Fig. 4.3.2.

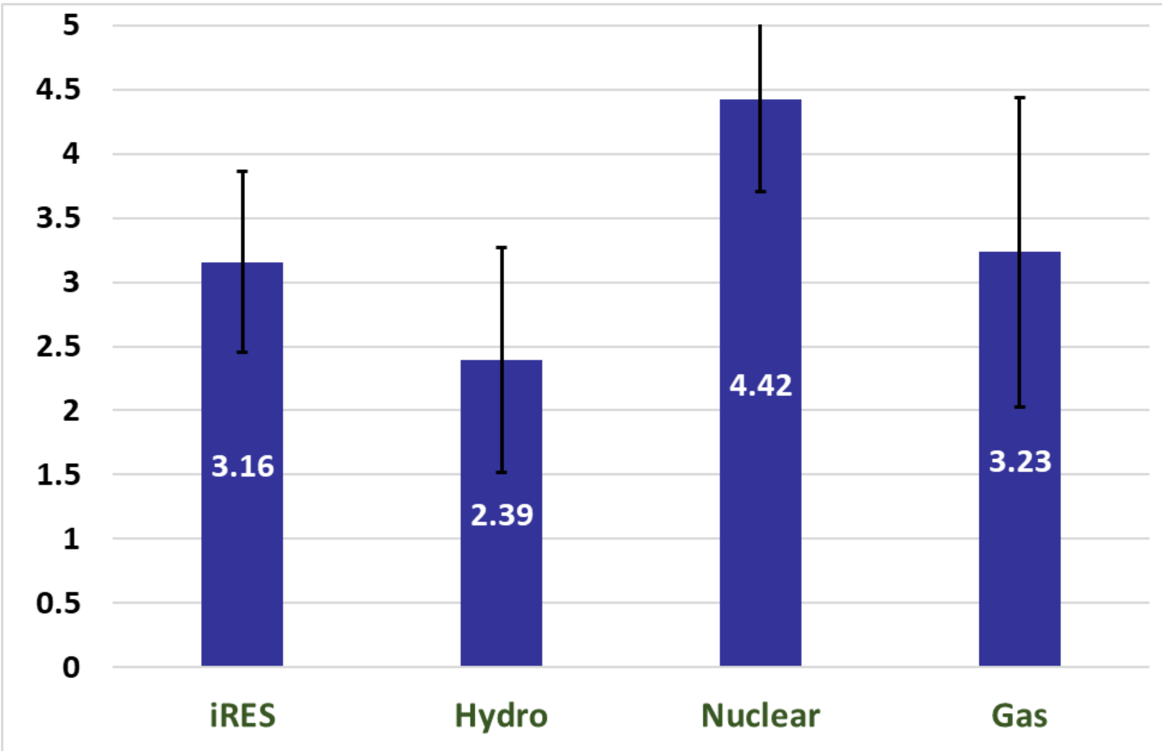


Fig. 4.3.2 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator I 3.1) Jobs created (S_i 3.1.2) Jobs in contributing industries

The assessment reveals that nuclear power scores the highest at 4.42, reflecting a significant positive impact on employment in contributing industries due to its complex and wide-ranging support needs. Intermittent renewables follow with a score of 3.16, indicating a moderate impact on related job creation. Natural gas scores 3.23, showing a significant but slightly lower impact compared to nuclear power. Hydropower scores the lowest at 2.39, suggesting a more limited effect on employment in supporting industries.

- Nuclear power (score: 4.42/5) scores the highest at 4.42, indicating a significant positive impact on jobs in contributing industries. The nuclear sector has a wide-reaching influence on various supporting industries, including specialized manufacturing, construction, engineering services, and safety technology. The complexity and high standards of nuclear energy projects drive demand for a broad range of supporting roles and services. The high score reflects the extensive economic ripple effect of the nuclear industry. The need for specialized equipment, materials, and services related to nuclear power plants results in substantial job creation across a variety of contributing industries. This indicates that nuclear power not only supports high-education jobs within the sector but also stimulates significant employment in associated sectors.

- Intermittent renewables (score: 3.16/5) score 3.16, showing a moderate impact on jobs in contributing industries. The renewable energy sector stimulates employment in related fields such as equipment manufacturing, construction of renewable installations, and maintenance services. However, the overall score is moderated by the relatively smaller scale of supporting industries compared to nuclear power. The score indicates that while intermittent renewables do positively affect job creation in related industries, the impact is less pronounced than in the nuclear sector. This reflects a smaller but still notable contribution to employment in supporting sectors, driven by the installation and maintenance of renewable energy technologies.

- Natural gas (score: 3.23/5) scores 3.23, suggesting a moderate positive impact on jobs in contributing industries (also showing a relatively dissensual rating – longer error bar). The natural gas industry generates employment in related sectors such as extraction, processing, transportation, and infrastructure development. The scale of employment in these supporting industries is significant but not as extensive as in the nuclear sector.
- Hydropower (score: 2.39/5) scores the lowest at 2.39, indicating a smaller impact on jobs in contributing industries. While hydropower projects do create jobs in areas such as dam construction and maintenance, the overall contribution to supporting industries is less significant compared to the other energy sectors. The low score suggests that hydropower has a more limited economic ripple effect on job creation in contributing industries. The specialized nature of hydropower projects results in fewer associated employment opportunities compared to sectors like nuclear power and natural gas, which have broader supporting industry impacts.

These results show that the nuclear power sector has the broadest economic ripple effect, driving substantial job creation in related industries. Intermittent renewables and natural gas also contribute to employment in supporting sectors, though to a lesser extent. Hydropower has the smallest impact on contributing industries, reflecting its more specialized and less expansive support network.

(I 3.2) Impact on the local/regional business (partner with other business)

The deployment of energy sources has several impacts on the local and regional economy. These impacts can be both positive and negative, depending on various factors such as the type of energy, the scale of deployment, the local market conditions, and the level of government support. The positive impacts are related to: (1) Job Creation, (2) Investment and Business Opportunities, (3) Energy Independence, (4) Increased Tax Revenues, (5) Environmental and Health Benefits. The categories of negative impacts are: (1) Disruption of Existing Industries, (2) Land Use and Environmental Concerns, (3) Grid Integration Challenges, (4) Initial Investment Costs.

The assessment on the sustainability performances for this indicator examines how different energy sectors foster partnerships and collaborations with local and regional businesses. This indicator reflects the degree to which an energy sector engages with and supports local economic activity through partnerships, collaborations, and business interactions. Higher scores suggest a *more positive impact on local and regional business networks*. The results are presented in Fig. 4.3.3.

The assessment reveals that nuclear power scores the highest at 4.47, indicating the most substantial positive impact on local and regional businesses through partnerships. This reflects the extensive collaboration required for nuclear power projects. Natural gas scores 2.93, showing a moderate level of impact with localized business interactions. Intermittent renewables and hydropower both score 2.89, suggesting a similar, moderate impact on local business partnerships, with local involvement primarily in construction and maintenance.

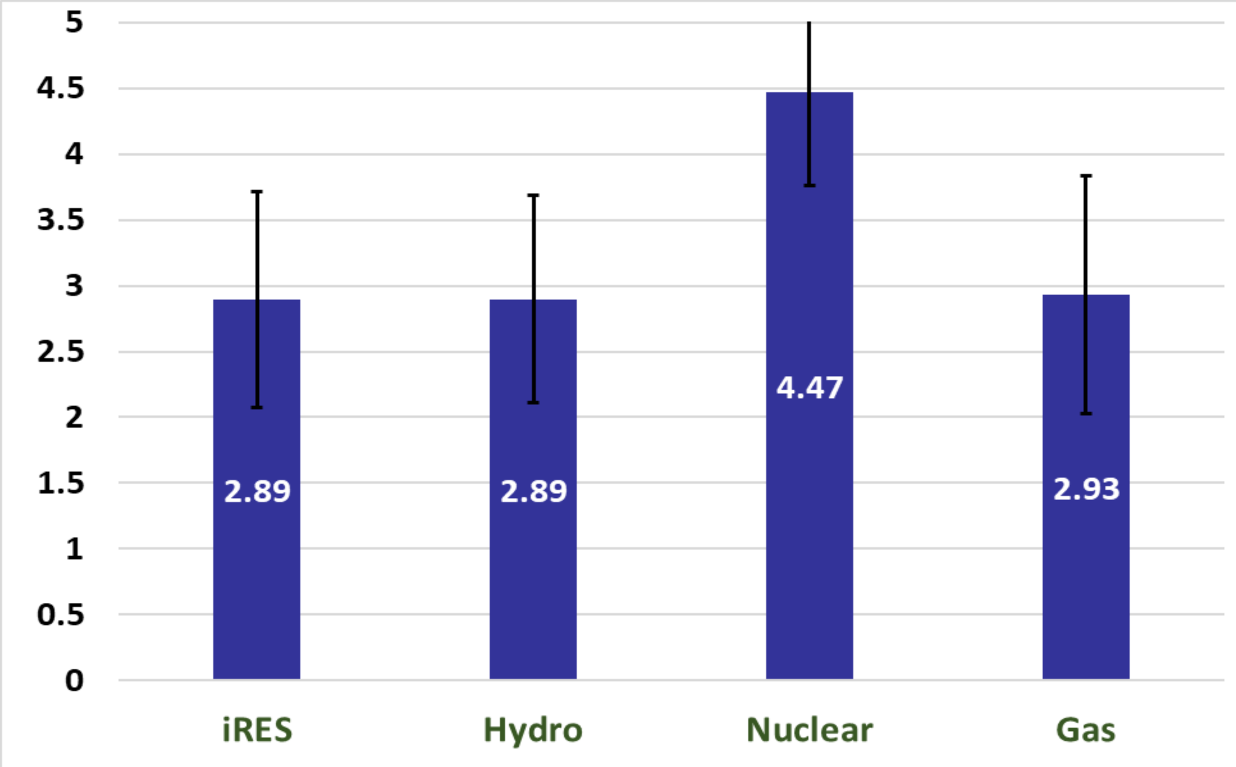


Fig. 4.3.3 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 3.2) Impact on the local/regional business (partner with other business)

- Nuclear power (score: 4.47/5) scores the highest at 4.47, indicating a strong positive impact on local and regional businesses through partnerships. The nuclear industry often involves extensive collaboration with local businesses for construction, maintenance, and supply chain activities. This includes partnerships for specialized equipment, safety services, and long-term operational support. The high score reflects the extensive network of local and regional businesses that interact with the nuclear industry. The complex nature of nuclear power plants necessitates significant local involvement, from construction firms to specialized service providers, enhancing the sector's positive impact on regional economic development.

- Natural gas (score: 2.93/5) scores 2.93, indicating an almost moderate impact on local and regional business partnerships. The natural gas industry does engage with local businesses for various needs such as infrastructure development, equipment supply, and service provision. However, the overall level of partnership is less pronounced compared to the nuclear sector. The industry does contribute to local economic activity, but the partnerships may not be as deep or extensive as those seen in the nuclear sector.

- Intermittent renewables (score: 2.89/5) score 2.89, reflecting a similar level of impact on local and regional businesses as hydro. While renewable energy projects do create opportunities for local partnerships, such as in construction and maintenance, the scale and nature of these interactions are more limited compared to nuclear power. The partnerships are generally focused on installation and maintenance, and while there are opportunities for local engagement, they do not have as broad an impact as seen with nuclear power.

- Hydropower (score: 2.89/5) also scores 2.89, showing a similar impact on local and regional businesses as intermittent renewables. Hydropower projects involve local businesses in areas like construction and maintenance, but the overall extent of these partnerships is not as significant as with the nuclear sector. The involvement of local businesses in the construction and maintenance phases of hydropower projects is notable, but the overall effect on the local economy is not as pronounced compared to nuclear power.

These results highlight that nuclear power has the most significant influence on local and regional business networks, with extensive partnerships and economic contributions. Natural gas, intermittent renewables, and hydropower also contribute to local business engagement, but to a lesser extent compared to the nuclear sector.

(I 3.3) Additional goods and services created

The assessment on the sustainability performances for this indicator examines the extent to which different energy sectors stimulate the creation of additional goods and services beyond their core operations. This indicator reflects the broader economic benefits that an energy sector can provide by fostering innovation, supporting ancillary industries, and generating new market opportunities. Higher scores indicate a *greater ability of the sector to create additional economic value through these additional goods and services*. The results are presented in Fig. 4.3.4.

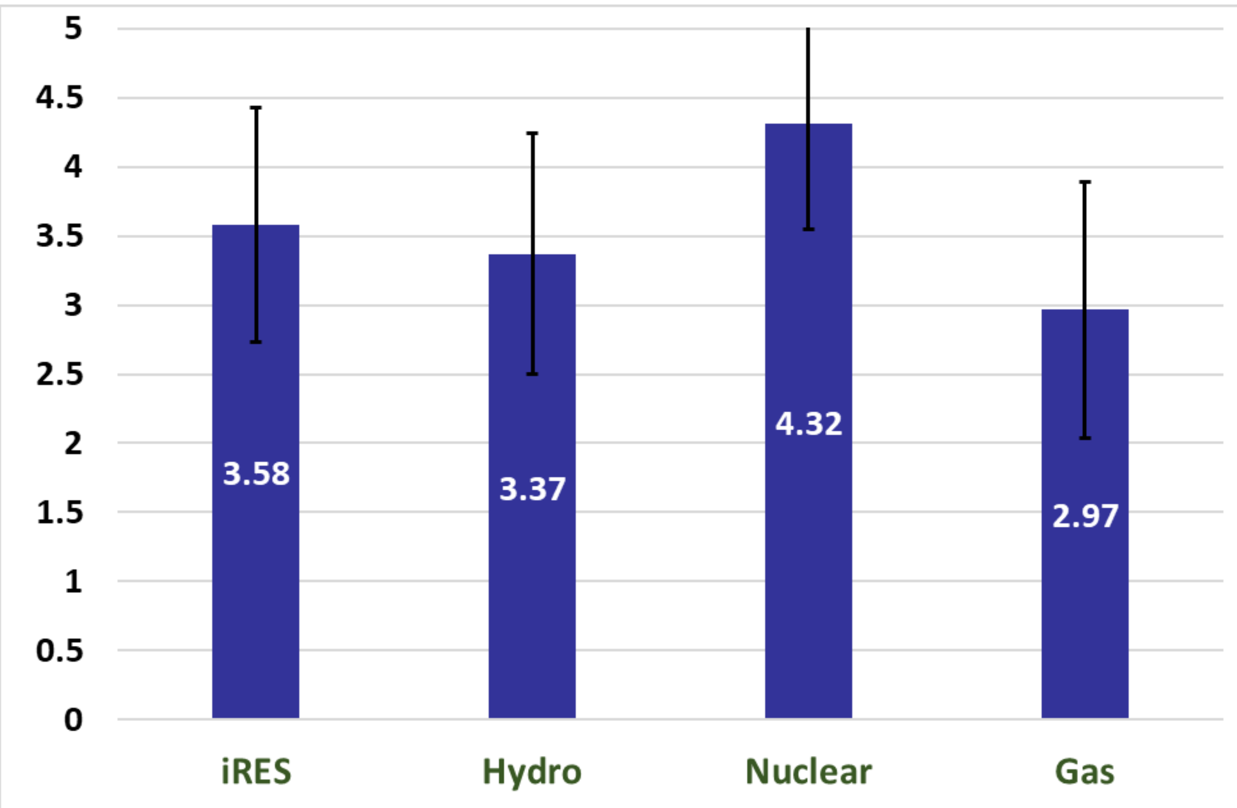


Fig. 4.3.4 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 3.3) Additional goods and services created

The assessment shows that nuclear power leads with a score of 4.32, reflecting its strong capability to generate additional goods and services through technological advancements and innovations. Intermittent renewables follow with a score of 3.58, indicating a significant impact on economic development and creation of new services and products. Hydropower scores 3.37, showing a moderate ability to create additional economic value, while natural gas scores the lowest at 2.97, reflecting a more limited impact on generating additional goods and services.

- Nuclear power (score: 4.32/5) scores the highest at 4.32, indicating a strong capacity to create additional goods and services. The nuclear industry often drives significant innovation and development in various technologies, such as advanced materials, safety systems, and high-precision engineering. This sector also generates substantial economic activity in the form of new businesses, services, and products related to its operations and technology needs. The complexity and high-tech nature of nuclear energy projects stimulate a wide range of ancillary industries, leading to the development of new products and services. This makes nuclear power a key driver of technological advancement and economic growth in related sectors.

- Intermittent renewables (score: 3.58/5) score 3.58, indicating a substantial positive impact on the creation of additional goods and services. The growth of renewable energy technologies has led to innovations in areas such as energy storage, grid management, and sustainable materials. Additionally, renewable energy projects often foster the development of new business models and services related to clean energy. The sector's expansion promotes advancements in various technologies and services, contributing to the creation of new markets and business opportunities. While not as high as nuclear power, intermittent renewables still make a notable impact on economic development through ancillary innovations.

- Hydropower (score: 3.37/5) scores 3.37, showing a moderate ability to create additional goods and services. While hydropower projects do stimulate some innovation and development, particularly in areas such as hydrological engineering and environmental management, the impact is somewhat less pronounced compared to nuclear power and intermittent renewables. The focus on large-scale infrastructure and resource management can lead to some new business opportunities, but the overall economic impact is more limited in comparison.

- Natural gas (score: 2.97/5) scores the lowest at 2.97, indicating a more limited impact on the creation of additional goods and services. While the natural gas industry does generate some ancillary economic activity, such as in infrastructure development and technology for extraction and processing, it does not create as extensive a range of additional goods and services as the other sectors. The industry's focus on extraction and processing does not drive as broad an array of innovations or ancillary services compared to nuclear power, intermittent renewables, or hydropower.

These results highlight that nuclear power and intermittent renewables are more effective in stimulating economic activity beyond their core operations, driving innovation and creating new market opportunities. Hydropower also contributes to economic development but to a lesser extent, while natural gas has the smallest impact on additional goods and services creation among the assessed energy sources.

(I 3.4) Value of the knowledge generated and maintained for the future

The knowledge generated and maintained by various energy technologies, including solar, wind, hydro, and nuclear power, holds immense value for the future. Each technology contributes unique insights that can drive advancements in science, engineering, sustainability, and other fields. Insights gained from energy technologies expand our understanding of materials, mechanics, physics, and other scientific disciplines. Engineering solutions developed for energy systems can influence broader engineering projects and infrastructure development.

The assessment on the sustainability performances for this indicator examines how different energy sectors contribute to the generation and preservation of valuable knowledge and expertise that can benefit future developments. This indicator reflects the sector's role in advancing scientific research, technological innovation, and the creation of knowledge that can be leveraged for future energy solutions and broader applications. Higher scores indicate a *greater contribution to maintaining and advancing this knowledge*. The results are presented in Fig. 4.3.5.

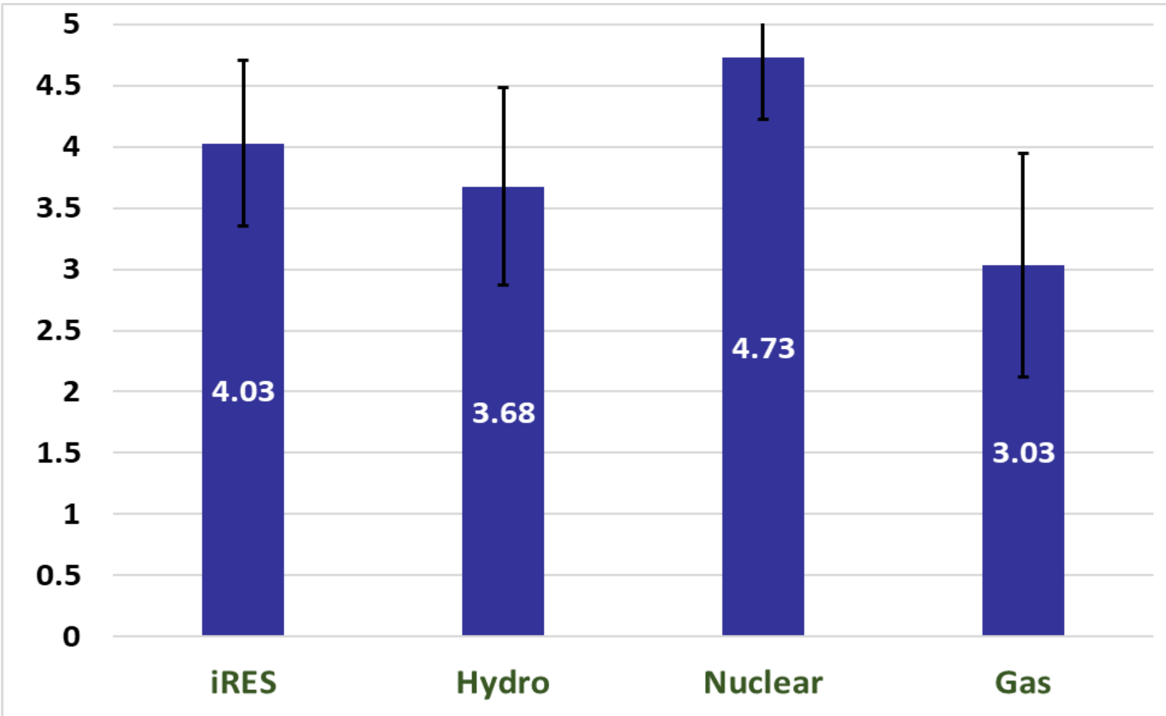


Fig. 4.3.5 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 3.4) Value of the knowledge generated and maintained for the future

The assessment indicates that nuclear power excels in generating and maintaining valuable knowledge for the future, scoring 4.73. This is due to its complex technology and rigorous research requirements. Intermittent renewables also make a significant contribution with a score of 4.03, reflecting their rapid technological advancements and innovations. Hydropower scores 3.68, showing a moderate impact with valuable but less dynamic knowledge generation. Natural gas scores the lowest at 3.03, reflecting a more limited role in pioneering new knowledge.

- Nuclear power (score: 4.73/5) scores the highest at 4.73, indicating a significant contribution to the generation and maintenance of valuable knowledge for the future. The nuclear sector is characterized by its complex technology, rigorous safety standards, and extensive research requirements. It generates substantial knowledge in fields such as nuclear physics, reactor design, waste management, and safety protocols, which are critical for advancing energy technology and ensuring safe operations. The sector's investment in research and development, coupled with its focus on safety and efficiency, ensures that the knowledge created is robust and has a lasting impact on future energy solutions and technological advancements.
- Intermittent renewables (score: 4.03/5) score 4.03, showing a strong contribution to knowledge generation and maintenance. This sector is rapidly evolving, with ongoing advancements in

technology, energy storage solutions, and integration with the grid. The focus on innovation in materials, efficiency improvements, and system integration contributes to a significant repository of knowledge that is valuable for future energy developments. The sector's dynamic nature and emphasis on technological improvement and sustainability contribute to a growing body of knowledge that will benefit future advancements in renewable energy and related technologies.

- Hydropower (score: 3.68/5) scores 3.68, indicating a moderate contribution to the generation and preservation of knowledge for the future. While hydropower technology is well-established and its principles are well-understood, there is still ongoing research into optimizing efficiency, environmental management, and integrating hydropower with other renewable sources. The score reflects the valuable knowledge that hydropower contributes, particularly in areas like environmental management and infrastructure optimization. However, compared to nuclear power and intermittent renewables, the scope of new knowledge generated is somewhat more limited due to the mature nature of hydropower technology.

- Natural gas (score: 3.03/5) scores the lowest at 3.03, indicating a more modest impact on the generation and maintenance of knowledge for the future. While the natural gas industry does contribute to advancements in extraction technology, efficiency improvements, and emissions management, it does not generate as extensive or innovative knowledge as the other sectors. The lower score of 3.03 suggests that the natural gas sector has a more limited role in advancing knowledge compared to nuclear power, intermittent renewables, and hydropower. The focus is primarily on optimizing existing technologies and managing environmental impacts rather than pioneering new fields of research.

These results suggest that nuclear power and intermittent renewables are leading in advancing and preserving critical knowledge that will benefit future energy solutions. Hydropower contributes valuable knowledge but no significant technological changes are expected, while natural gas has a more modest impact in terms of future knowledge generation and maintenance.

(I 3.5) Impact on education

The assessment on the sustainability performances for the indicator "Impact on Education" examines how different energy sectors contribute to educational opportunities, research, and training. This indicator reflects the role of each sector in promoting educational advancements, supporting academic programs, and fostering a skilled workforce through various educational initiatives. Higher scores indicate a *greater positive impact on education*. The results are presented in Fig. 4.3.6.

The assessment shows that nuclear power leads with a score of 4.74, reflecting its extensive impact on educational development through academic programs, research funding, and specialized training. Intermittent renewables follow with a strong score of 4.21, indicating significant contributions to education through advancements in technology and sustainability practices. Hydropower scores 3.58, showing a moderate impact with valuable but less dynamic educational contributions. Natural gas scores the lowest at 2.88, reflecting a more limited role in supporting educational initiatives and research.

- Nuclear power (score: 4.74/5) scores the highest at 4.74, reflecting a strong impact on education. The nuclear industry is deeply involved in academic and research institutions, supporting specialized educational programs in nuclear engineering, safety, and reactor technology. This sector contributes to substantial research funding, academic partnerships, and advanced training opportunities. The very high score highlights the nuclear sector's significant role in advancing education. The complexity and specialization of nuclear technology necessitate rigorous academic programs and research initiatives, making it a leading contributor to educational development in related fields.

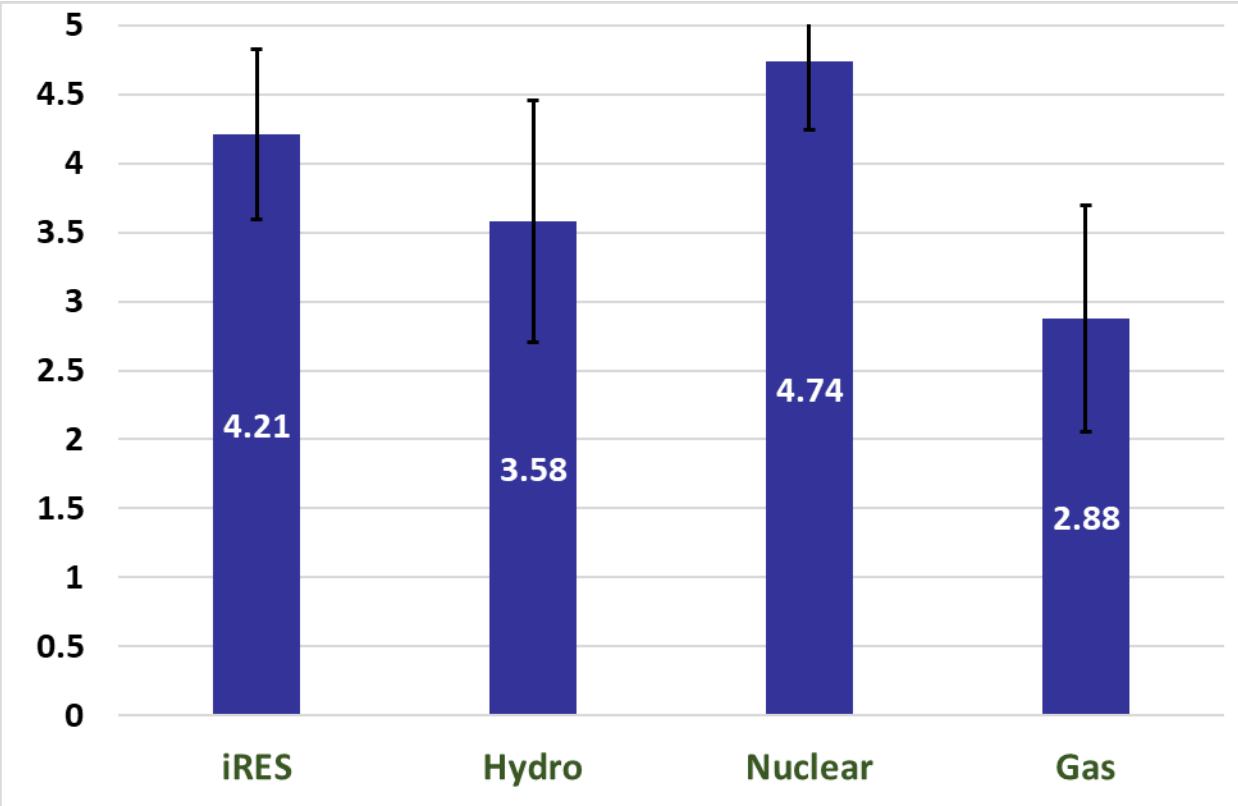


Fig. 4.3.6 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 3.5) Impact on education

- Intermittent renewables (score: 4.21/5) score 4.21, indicating a strong positive impact on education. The rapid growth of the renewable energy sector has led to increased investment in research, training programs, and educational initiatives focused on renewable technologies, energy efficiency, and sustainable practices. The score reflects the robust contribution of intermittent renewables to education. This sector drives innovation and creates educational opportunities through new technologies and sustainability practices, supporting a wide range of academic and vocational programs.

- Hydropower (score: 3.58/5) scores 3.58, showing a moderate impact on education. While the hydropower sector does contribute to educational programs and research, particularly in the areas of water management and environmental impact, the scale of its impact is somewhat less compared to nuclear power and intermittent renewables. The score suggests that hydropower has a valuable but more limited impact on education. The sector supports educational initiatives related to engineering and environmental studies, but the scope and scale of these contributions are less dynamic compared to the more rapidly evolving sectors.

- Natural gas (score: 2.88/5) scores the lowest at 2.88, indicating a relatively modest impact on education. The natural gas industry's contribution to educational programs and research is less pronounced compared to the other sectors. While it does support some training and research, particularly in areas like extraction technology and emissions management, the overall impact is more limited. The focus on optimizing existing technologies and managing environmental impacts does not generate as many educational opportunities or research initiatives compared to the other sectors.

These results highlight that nuclear power and intermittent renewables are leading in fostering educational development, while hydropower and natural gas have more limited but still notable impacts.

(I 3.6) Contribute to the reduction of inherited burdens (toxic wastes, military stocks)

Toxic waste refers to hazardous materials that can cause serious harm to human health and the environment if not managed and disposed of properly. Various sources are present, including industrial processes, agriculture, healthcare, and household products. Many countries faced challenges related to the cleanup and proper management of toxic waste sites, such as abandoned industrial facilities and landfills containing hazardous materials. These sites can leach pollutants into soil and water, posing significant health risks to nearby communities and ecosystems.

Military stocks refer to excess or obsolete weapons, ammunition, and other military equipment that were accumulated during periods of conflict or heightened military buildup. These surplus military stocks can present challenges when it comes to storage, disposal, and preventing their illicit spread. Such stocks might include unexploded ordnance, aging chemical weapons, and radioactive materials. International treaties and agreements have been established to manage and eliminate certain categories of military stocks. For instance, the Chemical Weapons Convention aims to eliminate chemical weapons and their production facilities, while various arms control agreements aim to reduce the stockpiling of conventional weapons.

The assessment on the sustainability performances for this indicator examines how different energy sectors address and mitigate historical environmental and safety issues, including the management of toxic wastes and military stockpiles. This indicator reflects each sector's effectiveness in contributing to the reduction of these inherited burdens. Higher scores indicate a *greater positive impact on addressing and mitigating such burdens*. The results are presented in Fig. 4.3.7.

The assessment shows that nuclear power leads with a score of 3.72, indicating a significant role in developing advanced solutions to reduce the inherited burdens. Intermittent renewables follow with a score of 3.06, showing a positive contribution to reducing burdens through decreased fossil fuel dependence, despite some lifecycle impacts. Hydropower scores 2.70, reflecting a moderate impact with limited direct reduction of inherited burdens, but notable environmental effects associated with its operation. Natural gas scores the lowest at 2.06, indicating the least contribution to reducing inherited burdens, primarily due to its reliance on fossil fuels and associated environmental impacts.

- Nuclear power (score: 3.72/5) scores 3.72, reflecting a significant contribution to the reduction of inherited burdens. While nuclear power does generate radioactive waste, the industry is actively involved in developing advanced waste management technologies and methods for safe disposal and long-term storage, including the development of solution to burn the accumulated wastes or to transmute the radioactive isotopes. Additionally, nuclear energy can play a role in reducing the military stocks (such as excess or obsolete weapons, including the Plutonium stocks), and in reducing reliance on fossil fuels, which helps mitigate broader environmental burdens.

- Intermittent renewables (score: 3.06/5) score 3.06, showing a moderate contribution to reducing inherited burdens reflecting that intermittent renewables contribute positively to reducing inherited burdens by lessening reliance on traditional fossil fuels and lowering emissions.

However, the impact is moderated by the environmental considerations associated with the lifecycle of renewable technologies.

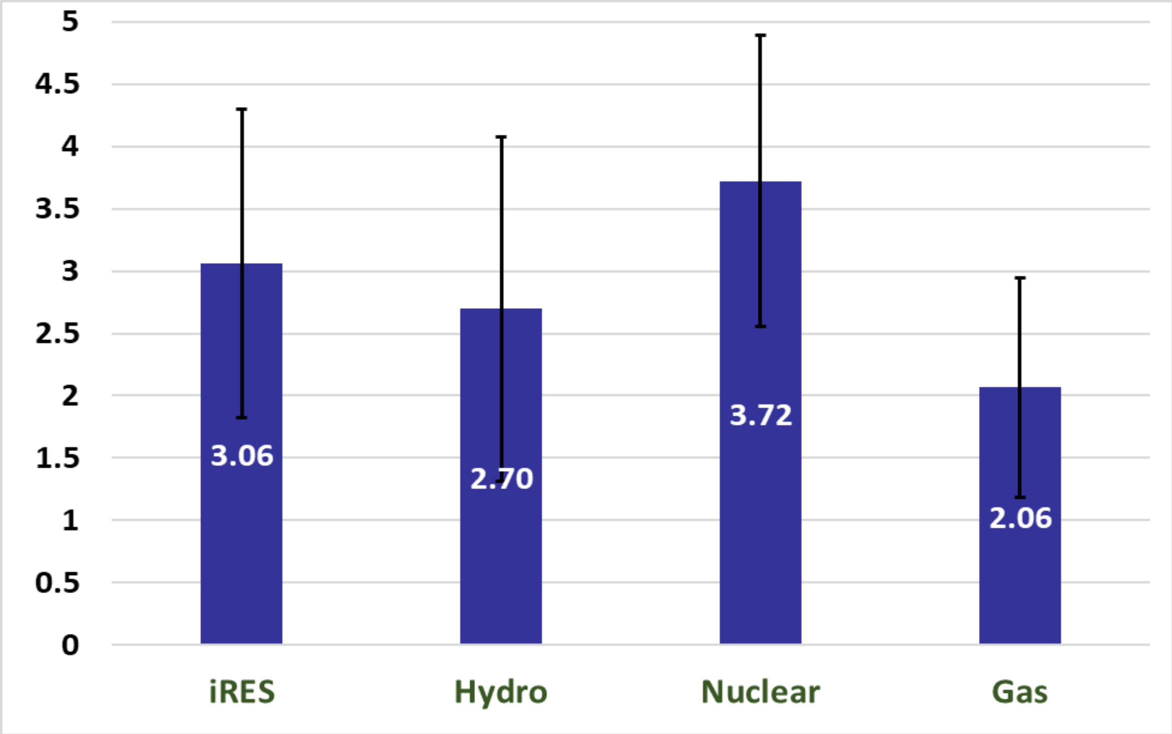


Fig. 4.3.7 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 3.6) Contribute to the reduction of inherited burdens (toxic wastes, military stocks)

- Hydropower (score: 2.70/5) scores 2.70, indicating a lower impact on reducing inherited burdens compared to other sectors. The score suggests that hydropower has a more limited impact on addressing inherited burdens. Although it avoids generating some types of waste, the environmental effects associated with large-scale hydropower projects contribute to its lower score. The relatively dispersed ratings (longer error bar) may indicate differential knowledge or sensitivities among the respondents.

- Natural gas (score: 2.06/5) scores the lowest at 2.06, indicating the least contribution to reducing inherited burdens. While natural gas is a cleaner fossil fuel compared to coal or oil, it still involves the extraction, processing, and combustion of fossil resources, which contribute to environmental and health issues. Additionally, the sector does not directly address toxic wastes or military stockpiles. The ongoing environmental impacts associated with fossil fuel extraction and use, combined with the sector's limited focus on addressing historical burdens, contribute to its lower score.

These results highlight that nuclear power is more effective in addressing inherited environmental and safety issues compared to the other considered technologies.

(I 3.7) Impact on health improvement

The impact of the energy technologies on health improvement can be assessed comparatively, considering various factors such as air and water pollution, safety risks, and long-term health benefits. Solar and wind technologies have a generally positive impact on health due to their minimal emissions and low safety risks. Hydroelectric energy can also contribute positively to health if its environmental impacts are carefully managed. Nuclear energy, while low in emissions, carries potential health risks associated with accidents. On the other hand, the development of nuclear sector contributed a lot to the development of nuclear medicine (radiopharmaceuticals, imaging procedures, diagnostic applications, therapeutic applications, etc.) with high benefits on the health improvement.

The assessment on the sustainability performances for this indicator examines how different energy sources contribute to improving public health. This includes factors such as reductions in air and water pollution, lower emissions of harmful substances, and overall improvements in environmental quality that positively affect human health. Higher scores indicate a *more significant positive impact on health improvement*. The results are presented in Fig. 4.3.8.

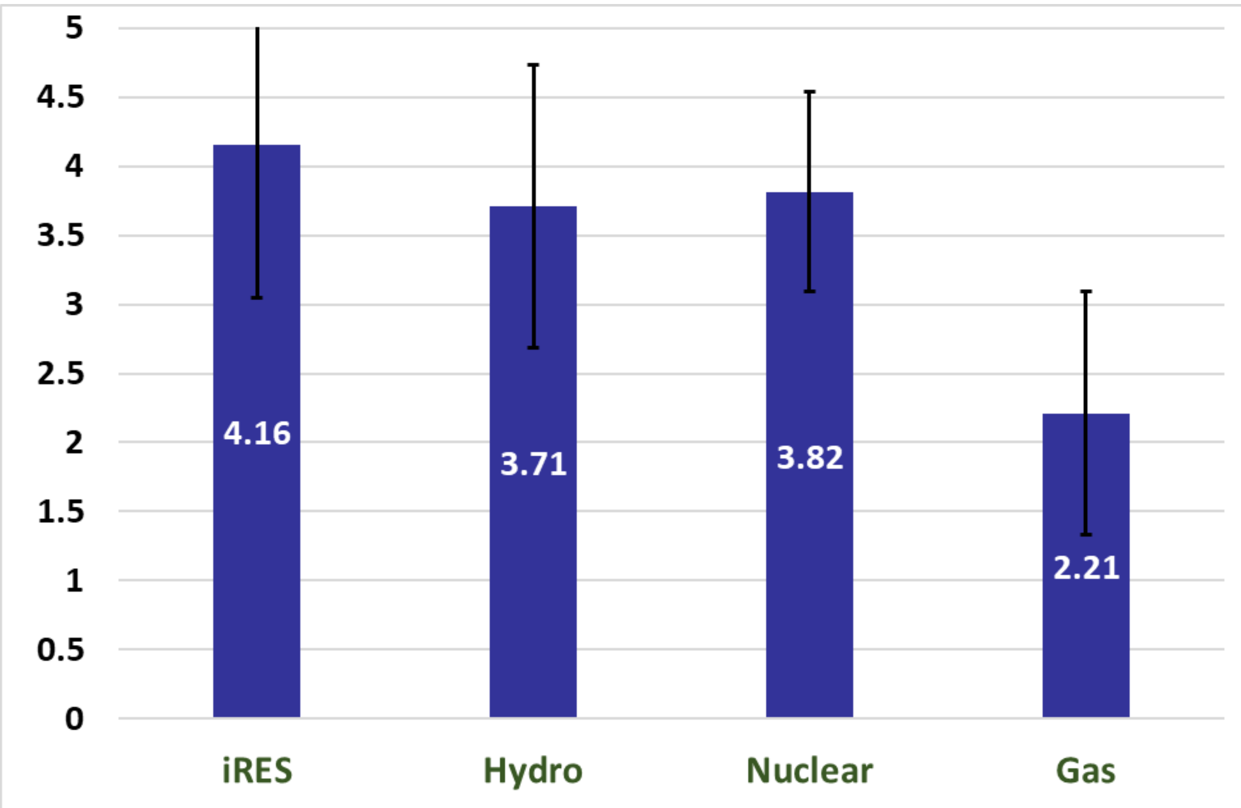


Fig. 4.3.8 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 3.7) Impact on health improvement

The assessment reveals that intermittent renewables score the highest at 4.16, indicating their strong positive impact on health improvement through reduced pollution and minimal environmental impacts. Nuclear power scores 3.82, reflecting its benefits in reducing air pollution, and contribution to the development of nuclear medicine, though balanced by the risks associated with radioactive materials. Hydropower follows closely with a score of 3.71, showing a positive health impact but moderated by environmental considerations. Natural gas scores the lowest at 2.21, highlighting its relatively lower contribution to health improvement due to its emissions and environmental risks.

- Intermittent renewables (score: 4.16/5) score the highest at 4.16, reflecting their strong positive impact on health improvement. These energy sources produce minimal direct emissions and do not contribute to air or water pollution during their operational phase. This leads to significant reductions in health issues related to pollution, such as respiratory and cardiovascular diseases. By reducing dependence on fossil fuels and minimizing pollution, these energy sources contribute significantly to healthier environments and communities.

- Nuclear power (score: 3.82/5) scores 3.82, indicating a considerable positive impact on health improvement. Nuclear plants do not emit greenhouse gases or air pollutants during operation, which helps to reduce health problems associated with air pollution. However, the potential risks related to radiation exposure and the management of radioactive waste slightly temper its overall impact on health. The score of 3.82 reflects that nuclear power contributes positively to public health by reducing air pollution, also by nuclear medicine developed techniques. However, the risks associated with nuclear accidents and waste management are factors that prevent it from scoring as high as intermittent renewables.

- Hydropower (score: 3.71/5) scores 3.71, showing a positive impact on health improvement. Like other renewable energy sources, hydropower does not produce air pollutants during its operation. However, the construction and operation of large dams can lead to changes in local ecosystems and water quality, which may have indirect health impacts on nearby communities.

- Natural gas (score: 2.21/5) scores the lowest at 2.21, indicating a relatively low positive impact on health improvement. Although natural gas burns cleaner than coal or oil, it still contributes to air pollution through the emission of nitrogen oxides (NOx) and other pollutants. Methane leaks during extraction and distribution also pose significant environmental and health risks, contributing to respiratory and cardiovascular problems. The score reflects that while natural gas is cleaner than other fossil fuels, it still poses considerable health risks due to its pollutant emissions and methane leaks. This limits its ability to significantly improve public health compared to other energy sources.

These results underscore the health benefits of transitioning to cleaner energy sources, with intermittent renewables leading the way in terms of their potential to improve public health.

(I 3.8) Impact on poverty

The impact of these energy technologies on poverty is complex depending on several factors such as geographical location, scale of implementation, policy support, economic considerations, etc. While renewable energy sources like solar and wind often have more direct and widespread positive impacts on poverty through job creation and reduced energy costs, hydro and nuclear energy can have mixed effects that depend on careful management and community engagement.

The assessment on the sustainability performances for this indicator examines how different energy sources contribute to poverty reduction. This indicator considers factors such as access to affordable energy, job creation, economic development, and the overall effect of energy projects on the socioeconomic conditions of communities, especially in low-income areas. Higher scores indicate a *more significant positive impact on poverty alleviation*. The results are presented in Fig. 4.3.9.

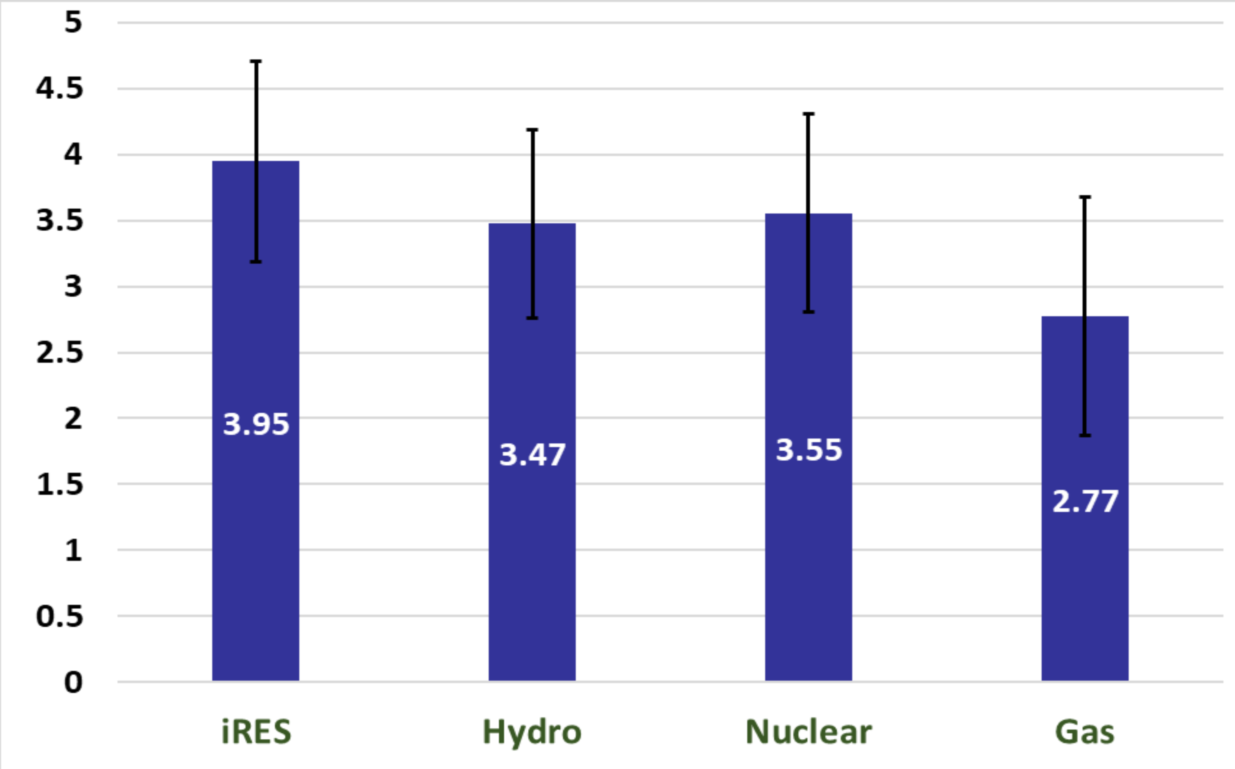


Fig. 4.3.9 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 3.8) Impact on poverty

The assessment reveals that intermittent renewables score the highest at 3.95, highlighting their strong role in poverty reduction through job creation and improved access to energy in underserved areas. Nuclear power scores 3.55, reflecting its potential to contribute to economic development and poverty reduction, though with some limitations due to its high costs and long development periods. Hydropower scores 3.47, indicating a positive impact on poverty, albeit tempered by potential social and environmental challenges. Natural gas scores the lowest at 2.77, showing that while it can aid in economic development, its impact on poverty reduction is relatively limited, especially due to energy price volatility and centralized benefits.

- Intermittent renewables (score: 3.95/5) score the highest at 3.95, indicating a strong positive impact on poverty reduction. These energy sources often involve decentralized energy production, which can provide electricity to remote and underserved areas, improving access to energy. The growth of the renewable energy sector also creates jobs, both directly in manufacturing, installation, and maintenance, and indirectly in supporting industries. The high score suggests that intermittent renewables are highly effective in reducing poverty. By improving access to energy, particularly in remote or impoverished regions, and creating job opportunities, renewables can significantly contribute to economic upliftment and poverty alleviation.

- Nuclear power (score: 3.55/5) scores 3.55, reflecting a considerable impact on poverty reduction. Nuclear projects often bring significant investments, infrastructure development, and long-term employment opportunities to the regions where they are located. However, the high capital costs and long development timelines mean that the benefits might not be as accessible to poorer communities in the short term. The score indicates that while nuclear power has the potential to contribute to poverty reduction through job creation and economic development, the benefits may be more concentrated in areas with the resources to support such large-scale projects, and the delayed nature of these benefits limits its impact.

- Hydropower (score: 3.47/5) scores 3.47, indicating a positive but slightly lower impact on poverty reduction compared to renewables and nuclear. Large hydropower projects can create jobs and provide long-term, low-cost electricity, which can help reduce energy poverty. However, the social and environmental impacts, such as displacement of communities and changes in local ecosystems, can also create challenges for poverty reduction. The score reflects that hydropower contributes to poverty reduction by providing stable, affordable energy and creating jobs. However, the potential negative impacts on local communities, such as displacement, can mitigate some of these benefits, leading to a slightly lower score.
- Natural gas (score: 2.77/5) scores the lowest at 2.77, indicating a relatively lower impact on poverty reduction. While natural gas can contribute to economic development and provide jobs, its benefits are often more centralized and may not reach the poorest communities. Additionally, the volatility of natural gas prices can lead to energy insecurity, which disproportionately affects low-income households. The score suggests that while natural gas can contribute to economic development, its impact on poverty reduction is limited. The centralization of benefits and potential for energy price fluctuations reduce its effectiveness in lifting people out of poverty compared to other energy sources.

These results suggest that while all energy sources can contribute to poverty alleviation to some degree, decentralized and accessible energy sources like intermittent renewables may offer the most immediate and widespread benefits for reducing poverty.

(I 3.9) Social level adoption of the technology

The assessment on the sustainability performances for the indicator “Social Level Adoption of the Technology” examines how readily different energy technologies are accepted and supported by the public and society at large. This includes factors like public perception, social acceptance, ease of integration into daily life, and potential resistance due to environmental, safety, or social concerns. Higher scores indicate *greater social acceptance and adoption of the technology*. The results are presented in Fig. 4.3.10.

The assessment highlights that intermittent renewables are the most socially accepted technology, scoring 4.18, due to their positive environmental impact, potential for local energy solutions, and strong public support for sustainability. Hydropower follows with a score of 3.89, reflecting its reliability and renewable nature, though concerns about environmental and social impacts slightly reduce its acceptance. Natural gas scores 3.03, showing moderate acceptance as a cleaner fossil fuel, but its environmental risks limit full public support. Nuclear power, with a score of 2.84, faces the most significant social resistance, primarily due to safety concerns and the long-term challenges of waste management.

- Intermittent renewables (score: 4.18/5) score the highest at 4.18, indicating strong social acceptance and adoption. These technologies are often viewed positively due to their environmental benefits, such as reducing greenhouse gas emissions and reliance on fossil fuels. Additionally, the decentralized nature of renewable energy can empower communities by providing local energy solutions and reducing dependence on large, centralized power plants. The high score of 4.18 suggests that intermittent renewables enjoy broad public support, driven by their environmental benefits and potential for local empowerment. Their visibility in reducing carbon footprints and promoting sustainability makes them highly favored by society, leading to widespread adoption and acceptance.

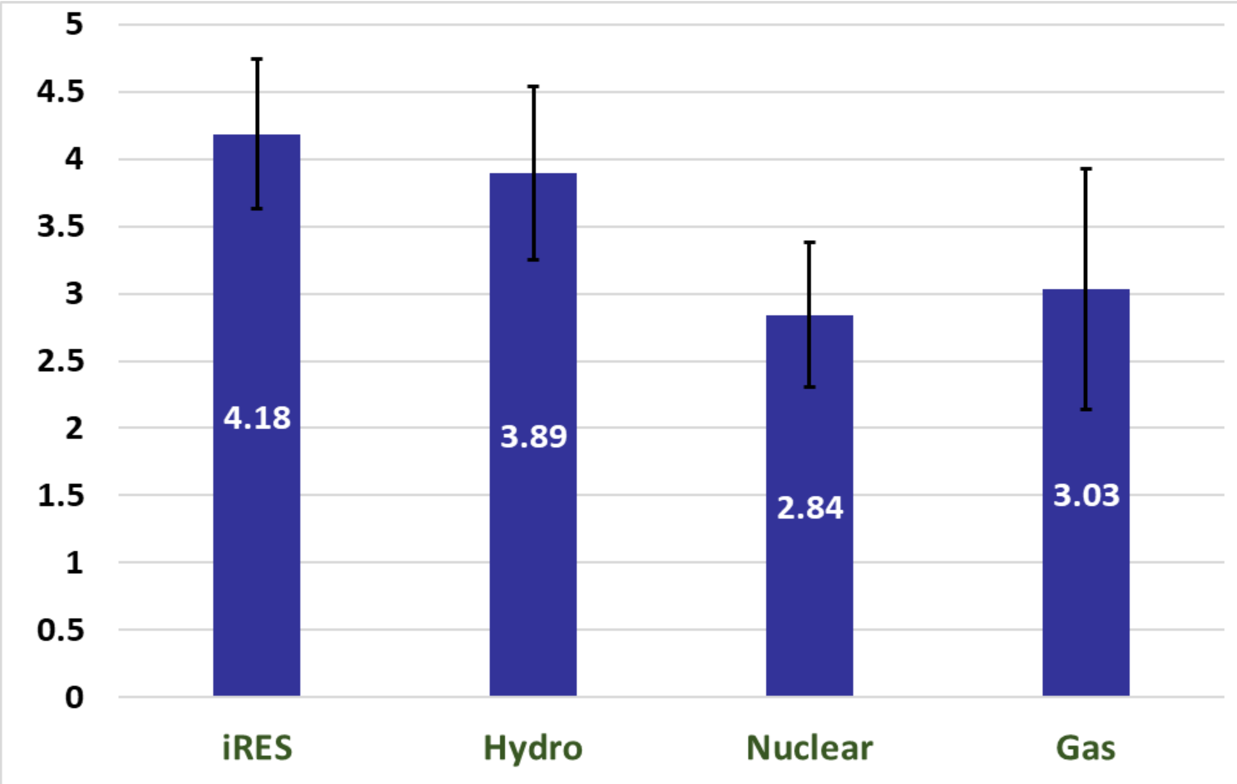


Fig. 4.3.10 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 3.9) Social level adoption of the technology

- Hydropower (score: 3.89/5) scores 3.89, reflecting a high level of social acceptance. As a long-established technology, hydropower is often viewed as a reliable and clean source of energy. However, its social acceptance can be tempered by concerns over environmental impacts, such as ecosystem disruption, fish populations, and displacement of local communities due to large dam projects. The score indicates strong social acceptance, particularly due to its reliability and contribution to renewable energy. However, the environmental and social concerns associated with large-scale hydro projects can lead to some resistance, slightly lowering its overall acceptance compared to intermittent renewables.
- Natural gas (score: 3.03/5) scores 3.03, indicating moderate social acceptance. While natural gas is often viewed as a cleaner alternative to coal and oil, contributing to a reduction in greenhouse gas emissions, concerns over its contribution to climate change, particularly through methane leaks, and the environmental impacts of extraction methods like fracking can dampen public support. The score of 3.03 reflects that while natural gas is accepted as a relatively cleaner fossil fuel and a bridge in the transition to renewable energy, its association with environmental risks and climate change concerns limits its full social acceptance. Public opinion is divided, with some viewing it as a necessary interim solution, while others are concerned about its long-term environmental impacts.
- Nuclear power (score: 2.84/5) scores the lowest at 2.84, indicating relatively low social acceptance. Despite its benefits, such as low greenhouse gas emissions and high energy output, nuclear power faces significant public resistance due to concerns over safety, particularly in the

wake of high-profile accidents like Chernobyl and Fukushima, and the challenges of radioactive waste management. Additionally, the long-term environmental risks associated with nuclear waste and the high costs of decommissioning add to public apprehension. The score suggests that nuclear power struggles with social acceptance, largely due to safety concerns and the potential catastrophic consequences of accidents. Despite its role in reducing carbon emissions, these risks lead to a lower level of public support, making it less socially adopted compared to other energy sources.

These scores suggest that technologies perceived as safer and more environmentally friendly are more readily accepted by the public, with renewables leading the way, while technologies associated with higher risks or environmental concerns, like nuclear power and natural gas, face greater challenges in social adoption.

(I 3.10) Existing investment in RDI to develop the technology

Investments in Research, Development, and Innovation (RDI) for different energy technologies are dependent on the technology maturity, regulatory environments, targeted performances.

The assessment on the sustainability performances for this indicator examines how much investment has been made in research, development, and innovation to advance the respective energy technologies. Higher scores reflect *stronger investment,* indicating a greater focus on improving the technology, increasing efficiency, reducing costs, and addressing sustainability concerns. The results are presented in Fig. 4.3.11.

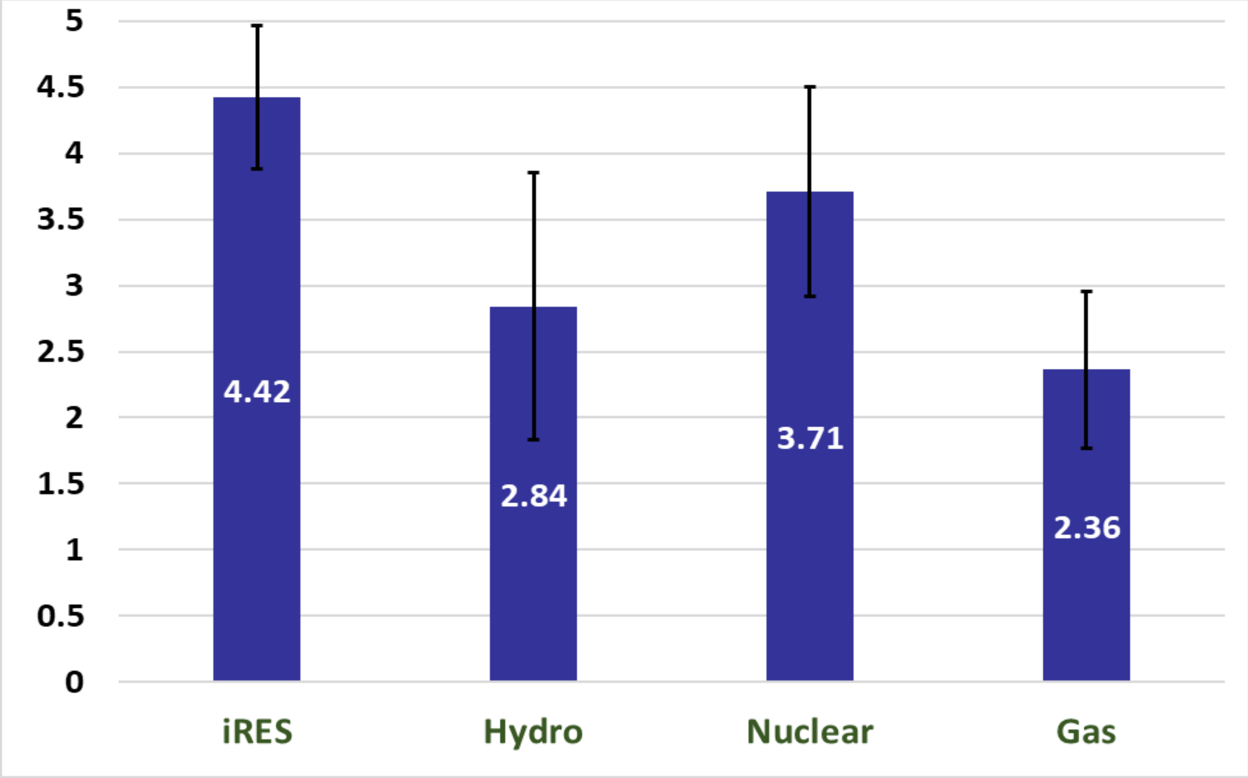


Fig. 4.3.11 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 3.10) Existing investment in RDI to develop the technology

The assessment shows that intermittent renewables lead in RDI investment, with a score of 4.42, highlighting the strong global focus on advancing these technologies to meet future energy needs sustainably. Nuclear power, with a score of 3.71, also receives substantial RDI investment, particularly aimed at addressing safety and waste management issues. Hydropower scores 2.84, reflecting its mature status and the moderate level of RDI needed for incremental improvements. Natural gas scores the lowest at 2.36, indicating limited RDI investment, likely due to its established technology and the shifting focus towards more sustainable energy sources.

- Intermittent renewables (score: 4.42/5) score the highest at 4.42. This high score reflects the significant global investment in research, development, and innovation aimed at improving these technologies. The push to enhance efficiency, lower costs, improve energy storage solutions, and integrate these technologies into existing grids has driven substantial RDI efforts. Governments, private companies, and international organizations have invested heavily in advancing these technologies, driven by the global shift towards decarbonization and the urgent need to mitigate climate change. The score indicates that intermittent renewables are at the forefront of RDI investment, with considerable resources being allocated to advancing these technologies. This high level of investment is crucial for overcoming the inherent challenges of intermittency and storage, and for driving down costs to make renewable energy more competitive with traditional energy sources. The strong RDI focus also suggests that these technologies will continue to improve and play a central role in the future energy landscape.

- Nuclear power (score: 3.71/5) receives a score of 3.71, reflecting substantial but more moderate investment in RDI compared to intermittent renewables. Investment in nuclear RDI focuses on several key areas: improving reactor safety, developing advanced reactor designs (such as small modular reactors, SMRs), enhancing waste management solutions, and increasing the overall efficiency of nuclear power plants. The relatively high score indicates ongoing efforts to address the significant challenges associated with nuclear energy, including safety concerns and long-term waste management. The score suggests that nuclear power continues to attract significant RDI investment, aimed at making the technology safer, more efficient, and more sustainable. This investment is critical for addressing the public and environmental concerns that have historically hindered the broader acceptance and deployment of nuclear energy. The ongoing innovation in nuclear technology could potentially lead to safer and more economically viable solutions in the future.

- Hydropower (score: 2.84/5) scores 2.84, indicating a moderate level of investment in RDI. While hydropower is a mature and well-established technology, the relatively lower score suggests that there is less focus on research and innovation compared to other energy technologies. Most RDI efforts in hydropower are likely directed towards improving efficiency, reducing environmental impacts, and developing small-scale or innovative hydropower solutions, such as run-of-river systems that minimize ecological disruption. The score reflects the fact that hydropower, being a mature technology, may not require as much RDI investment as newer or more complex technologies. However, there is still a need for ongoing research to address environmental concerns, improve operational efficiency, and develop more sustainable and flexible hydropower solutions. The moderate investment suggests that while hydropower remains important, it may not be the primary focus of innovation in the current energy transition.

- Natural gas (score: 2.36/5) scores the lowest at 2.36, indicating relatively limited investment in RDI compared to other energy technologies. The lower score suggests that natural gas, as a well-established and widely used energy source, receives less focus in terms of innovation. While there is some investment in improving efficiency and reducing emissions (e.g., through carbon capture and storage technologies), natural gas is increasingly viewed as a transitional fuel rather than a long-term solution, which may explain the lower investment in its RDI. The score suggests that natural gas is not a major focus of current RDI investment, reflecting its status as a mature technology with less perceived need for innovation.

These scores suggest that investment in RDI is closely aligned with the perceived future role of each technology in the global energy mix, with renewables and nuclear energy receiving more attention as key components of a low-carbon future.

(I 3.11) Low dependency on government support (funding/ incentives, such as tax credits or subsidies)

The assessment on the sustainability performances for the indicator "Low Dependency on Government Support (funding/incentives, such as tax credits or subsidies)" examines the extent to which different energy sectors rely on government financial support to remain economically viable. Higher scores indicate *lower dependency*, reflecting the ability of the sector to operate and compete in the market without substantial government aid. The results are presented in Fig. 4.3.12.

The assessment reveals that hydropower has the lowest dependency on government support, with a score of 3.46, reflecting its mature market status and established infrastructure. Intermittent renewables and nuclear power both score 3.36, indicating a moderate dependency, with renewables gradually becoming more self-sufficient and nuclear power requiring ongoing government involvement due to its high costs. Natural gas scores the lowest at 3.27, showing a slightly higher reliance on government incentives, especially in areas where it is seen as a strategic or transitional energy source.

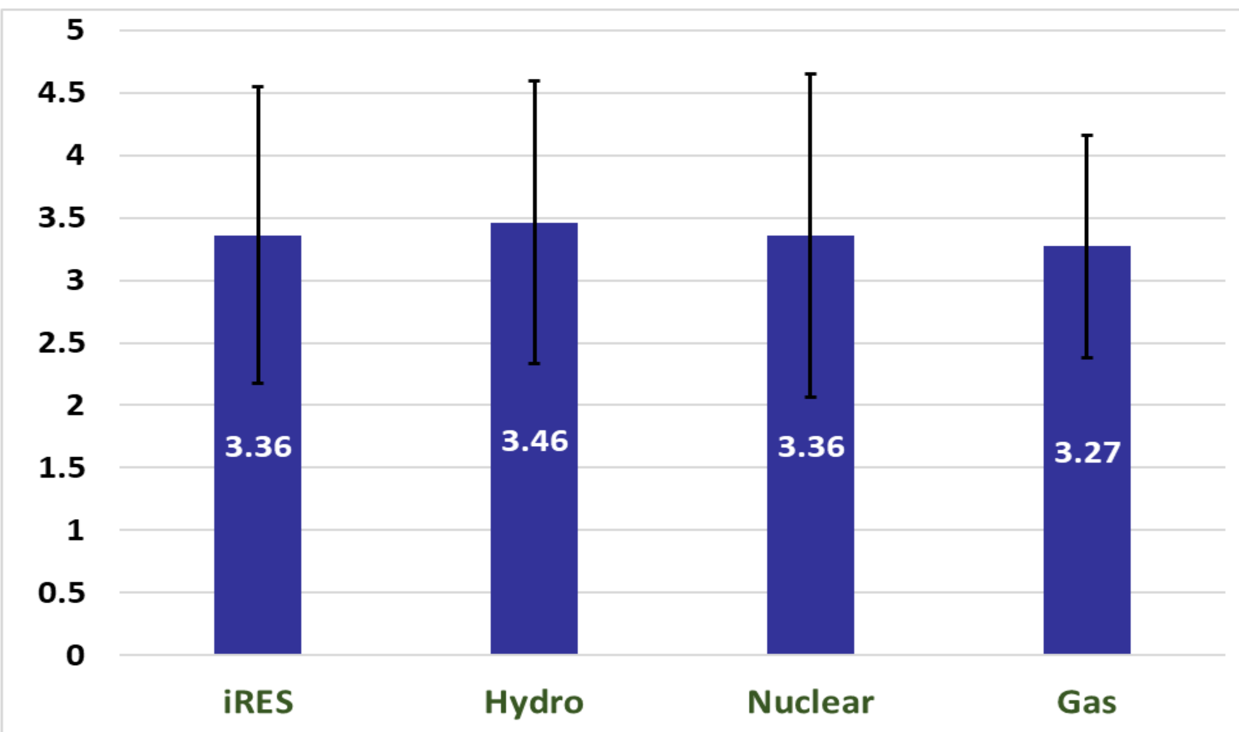


Fig. 4.3.12 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 3.11) Low dependency on government support (funding/ incentives, such as tax credits or subsidies)

- Hydropower (score: 3.46/5) scores the highest at 3.46, indicating the lowest dependency on government support among the considered sectors. Hydropower is a mature technology with established infrastructure, making it less reliant on ongoing government subsidies or incentives to remain competitive. The score suggests that hydropower can operate efficiently with minimal government support. The sector's long history and established market presence allow it to be more self-sustaining compared to other energy technologies.
- Intermittent renewables (score: 3.36/5) score 3.36, indicating a moderate dependency on government support (note also that there is some dispersion of opinion on this). While these technologies have benefited significantly from subsidies and incentives, their decreasing costs and increasing market penetration are gradually reducing their reliance on such support. The score reflects that intermittent renewables are transitioning towards greater economic self-sufficiency. However, they still rely on some level of government support, particularly in regions where market conditions or infrastructure are less favorable.
- Nuclear power (score: 3.36/5) also scores 3.36, indicating a level of dependency on government support similar to that of intermittent renewables (although this is the most dissensual result seen on this indicator). The nuclear industry often requires significant government involvement, particularly in the form of subsidies, guarantees, and research funding, due to the high costs and long timelines associated with nuclear projects. The score suggests a balanced dependency on government support. While nuclear energy is crucial for providing stable, low-carbon power, its economic viability often hinges on government backing, especially for new projects.
- Natural gas (score: 3.27/5) scores the lowest at 3.27, indicating, in the opinion of the respondents, a slightly higher dependency on government support compared to the other sectors. Although natural gas is a well-established energy source, it benefits from various forms of government incentives, including subsidies and tax credits, particularly in regions where it plays a strategic role in energy policy. The score suggests that while natural gas is competitive, it still relies on government support to some extent, particularly in areas where it serves as a transitional energy source or where its environmental impact needs to be mitigated through incentives.

These results may reflect the fact that hydropower is the most self-sufficient, while intermittent renewables and nuclear power are in the process of reducing their reliance on government support (both triggering a range of views and ratings from our respondents). Natural gas remains dependent on government backing, reflecting its strategic importance and the environmental challenges it faces.

(I 3.12) Risks, (S_i 3.12.1) Level of risk reflected in insurance needs

This indicator is reflecting the performance in safe and secure operation during entire life cycle. The metrics is expressed in the cost of insurance per unit of energy produced. The performance is very high for the lowest cost of insurance.

The assessment for this indicator examines the sustainability performance reflected by the degree of risk associated with each energy technology, as reflected in the cost and complexity of insurance coverage. A higher score indicates a *lower perceived risk*, leading to lower insurance needs. The results are presented in Fig. 4.3.13.

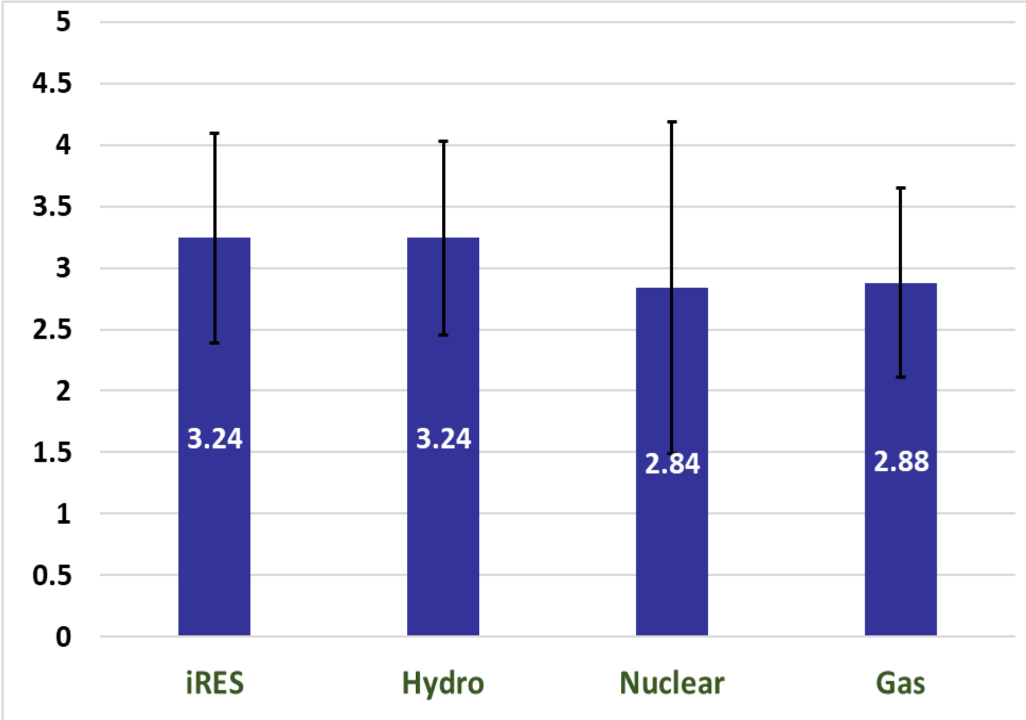


Fig. 4.3.13 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 3.12) Risks, (S_i 3.12.1) Level of risk reflected in insurance needs

From the results, the nuclear technology is considered as having the lowest performance (2.84), due to the great impact on environment and population in case of a severe core damage, as experienced with the Chernobyl accident or the Fukushima-Daiichi accident triggered by natural disaster. Even though the probability of the risk of a severe accident is very low, the consequences are very large, and the perception influencing the insurance policies thus penalizes nuclear. The raters may lend substantially different weight to these different components of risk (probability/impacts), which could explain the broad dispersion of opinion (longer error bar) observed. The best performance is obtained by iRES, and perhaps surprisingly, hydro (both with 3.24). We may surmise that many respondents considered small sized hydro plants and not the largest ones, the latter having the potential to cause very large impact in case of a dam failure followed by flooding, even though the probability of such breach is very low. This low probability/high consequence accident risk profile is conceptually comparable to that of nuclear; however the tight consensus on the hydro rating might indicate that raters are unaware of this similarity. Natural gas scores slightly lower at 2.88, reflecting significant insurance needs.

- Intermittent renewables (score: 3.24/5) have a score of 3.24, suggesting a moderate level of risk in terms of insurance needs. The risks associated with these technologies often stem from their reliance on weather conditions, potential damage from natural disasters (e.g., storms or hail for solar panels), and the complexities of integrating them into the grid. Insurance needs reflect these risks, particularly in areas prone to extreme weather events. The level of risk is seen as moderate, which is consistent with the generally lower operational risks but higher exposure to environmental factors.

- Hydropower (score: 3.24/5) also scores 3.24, indicating a similar level of risk as intermittent renewables. The risks in hydropower primarily relate to the potential for dam failures, which can have catastrophic consequences, and the environmental impact of altering water flows, which can lead to insurance costs. Additionally, hydropower projects may face risks related to geological stability, flooding, and the long-term impacts of climate change on water availability. The score reflects the significant but manageable risks associated with hydropower. While the technology is well-established, the large scale of infrastructure involved, coupled with environmental and geological risks, necessitates considerable insurance coverage. These factors contribute to the relatively high level of insurance needs.

- Natural gas (score: 2.88/5) scores 2.88, reflecting a higher level of perceived risk compared to renewables and hydropower. The primary risks associated with natural gas include explosions, leaks, and fires, as well as environmental and health impacts from emissions. The score suggests that natural gas is considered riskier from an insurance perspective.

Nuclear power (score: 2.84/5) has the lowest score at 2.84, indicating a high perception of risks, and consequently higher insurance needs among the technologies assessed. Dissensus nonetheless appears to be seen on whether insurance needs are correctly evaluated in light of the risk. These scores indicate that while all energy technologies carry inherent risks, the level of risk perceived and reflected in insurance needs varies based on the nature of the technology, its operational history, and the safety measures in place.

(I 3.12) Risks, (S_i 3.12.2) Proliferation of sensitive materials

The proliferation of sensitive materials in the energy sector refers to the potential spread of materials that could be used for both peaceful and non-peaceful purposes within the field of energy production.

Mainly the issue was raised by the nuclear energy sector referring to the potential spread of materials that are crucial to produce nuclear power, including both peaceful uses and the potential for weapons development. The spread of nuclear enrichment technologies and fissile materials raises concerns about the potential for countries or non-state actors to acquire the capabilities to build nuclear weapons. The main challenges and concerns are: (1) nuclear weapons proliferation (same materials used in civilian nuclear reactors, such as enriched uranium or plutonium, can be diverted for the production of nuclear weapons), (2) dual-use of technologies (both peaceful and military purposes), (3) security risks (the proliferation of sensitive materials can lead to security risks, including theft, sabotage, and attacks on nuclear facilities), (4) geopolitical tensions (proliferation can exacerbate geopolitical tensions, especially in regions where there are existing conflicts or power struggles).

The assessment for this indicator examines the effective measures for each energy technology to avoid potential spread or misuse of materials that could pose security threats. Higher scores indicate *more effective measures and a stronger commitment to non-proliferation*. The results are presented in Fig. 4.3.14.

The assessment shows that nuclear power scores the highest at 3.18, reflecting the necessity and effectiveness of robust non-proliferation measures due to the inherent risks of sensitive materials. Nonetheless, this assessment is not consensual (longer error bar). Intermittent renewables follow closely with a score of 3.16, highlighting their low but existing need for oversight, primarily related to supply chain risks. Hydropower scores 3.05, showing minimal proliferation concerns, mainly tied to large-scale project impacts. Natural gas scores the lowest at 3.03, indicating minimal risks associated with sensitive materials, with a primary focus on operational safety.

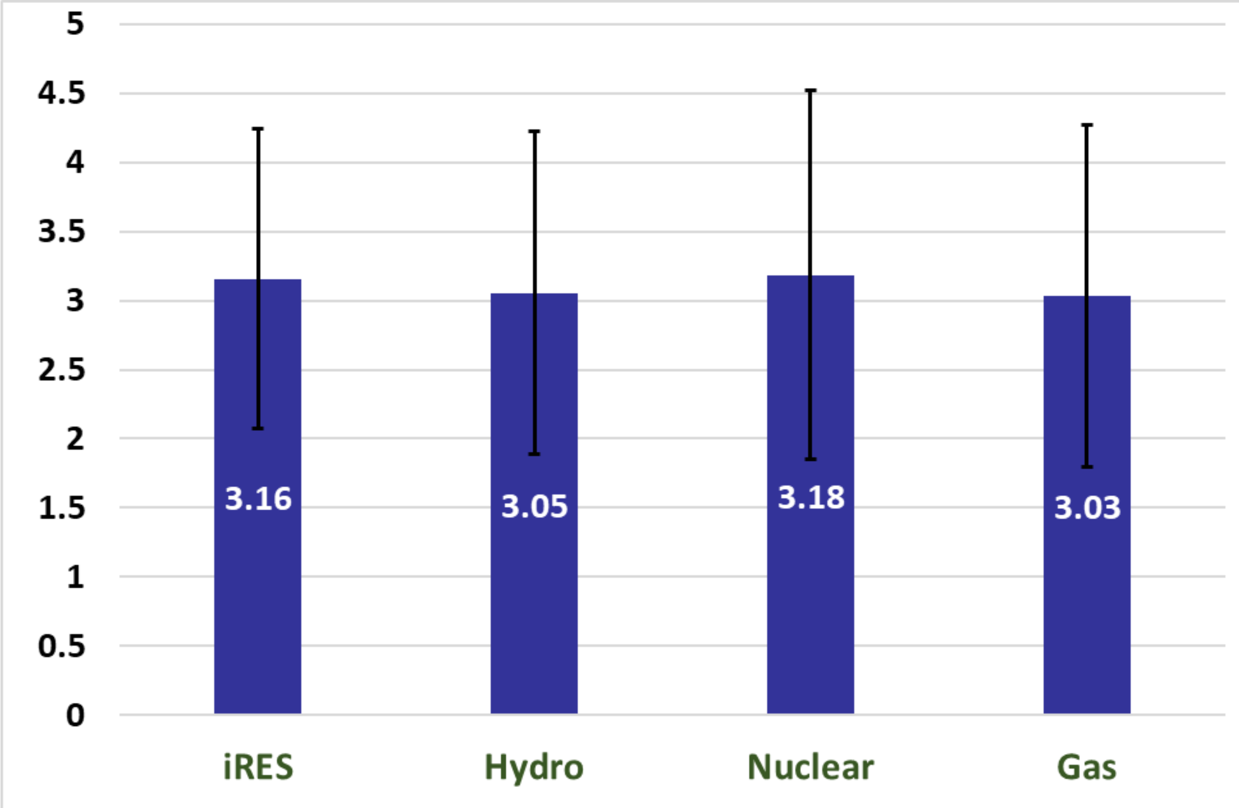


Fig. 4.3.14 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 3.12) Risks, (S_i 3.12.2) Proliferation of sensitive materials

- Nuclear power (score: 3.18/5) scores the highest at 3.18, indicating an average view of relatively effective measures for non-proliferation. The nuclear industry is subject to strict international regulations and monitoring by bodies such as the International Atomic Energy Agency (IAEA), which enforce controls on sensitive materials like uranium and plutonium. The score reflects that while nuclear power involves significant risks related to sensitive materials, the industry has robust measures in place to mitigate these risks. The dispersion of opinion however should not be ignored, indicating that raters do not assess in the same way the robustness or effectiveness of such measures. Alternatively, we could again find here a difference among raters concerning their sensitivity to probability of proliferation (a managed aspect of risk) or to the consequences of proliferation (which may overwhelm perceptions for some). Continuous improvement in regulatory frameworks and technology is essential to maintaining and enhancing these measures.

- Intermittent Renewables (score: 3.16/5) score 3.16, indicating that they have a minimal but present need for non-proliferation measures. While these technologies do not typically involve sensitive materials, the assessment may consider the supply chain and manufacturing processes, which could include the use of critical minerals that require oversight. The score suggests that while intermittent renewables generally have low risks associated with proliferation, there is still a need for effective measures in managing their supply chains and ensuring that any associated risks are minimized.

- Hydropower (score: 3.05/5) scores 3.05, reflecting a low to moderate need for non-proliferation measures. Hydropower infrastructure does not typically involve sensitive materials, but the score may reflect considerations around the environmental and geopolitical implications of large-scale projects. The score indicates that hydropower is generally secure regarding non-proliferation, with few concerns related to sensitive materials. However, the broader impacts of large-scale hydropower projects might necessitate some oversight and control. A dam may be used in a war based on the catastrophic potential of flooding.

- Natural Gas (score: 3.03/5) scores the lowest at 3.03, indicating a low but existing need for non-proliferation measures. While natural gas itself is not a sensitive material, the infrastructure and technologies used in extraction and processing might involve certain risks that require oversight. The primary focus in this sector is on ensuring safe and environmentally responsible practices rather than preventing the misuse of sensitive materials.

These results underscore that while nuclear power requires the most stringent non-proliferation measures, as well as possibly the need to make these measures better known, intermittent renewables, hydropower, and natural gas present significantly lower proliferation concerns, with the focus on ensuring responsible management of their specific risks.

(I 3.13) Equality of opportunities, (S_i 3.13.1) Women's empowerment

The exact share of women in the different energy sector varies by region, job role, and level of seniority. Women have often been underrepresented in technical and engineering roles within the energy sector.

The assessment of sustainability performances for this indicator examines how each energy technology sector contributes to gender equality and the empowerment of women, particularly in terms of employment opportunities, leadership roles, and overall inclusivity within the industry. Higher scores indicate a *higher contribution to gender equality and women's empowerment*. The results are presented in Fig. 4.3.15.

The assessment shows that nuclear power (3.34) leads in efforts towards women's empowerment, reflecting successful initiatives to integrate women into the workforce. Intermittent renewables (3.21) also show positive trends but still face challenges in achieving full gender equality, particularly in leadership. Hydropower (2.89) has room for improvement, with a need for more inclusive practices to increase women's participation. Natural gas (2.49) lags behind, indicating a need for significant reforms to promote gender equality and empower women in the industry.

- Nuclear power (score: 3.34/5) scores 3.34, the highest among the technologies assessed, indicating a relatively stronger commitment to women's empowerment. The nuclear industry has made concerted efforts in recent years to attract and retain more women, particularly in science, technology, engineering, and mathematics (STEM) roles. Initiatives to promote gender diversity and inclusion have been more prominent in the nuclear sector. The score reflects the positive impact of these efforts, with the nuclear industry increasingly recognizing the value of a diverse workforce. However, challenges remain in overcoming historical biases and ensuring that women have equal opportunities to advance into leadership roles within the industry.
- Intermittent renewables (score: 3.21/5) score 3.21, indicating a moderate level of contribution to women's empowerment. The renewables sector has been increasingly recognized for its potential to offer more inclusive opportunities for women, especially in emerging and innovative fields like clean energy technology, where there is a growing demand for a diverse workforce. The score suggests that while there are positive trends in women's participation in the renewables sector, challenges remain in fully integrating women into leadership roles and technical positions. The sector is seen as more progressive compared to traditional energy industries, but it still requires targeted efforts to enhance gender equality further.

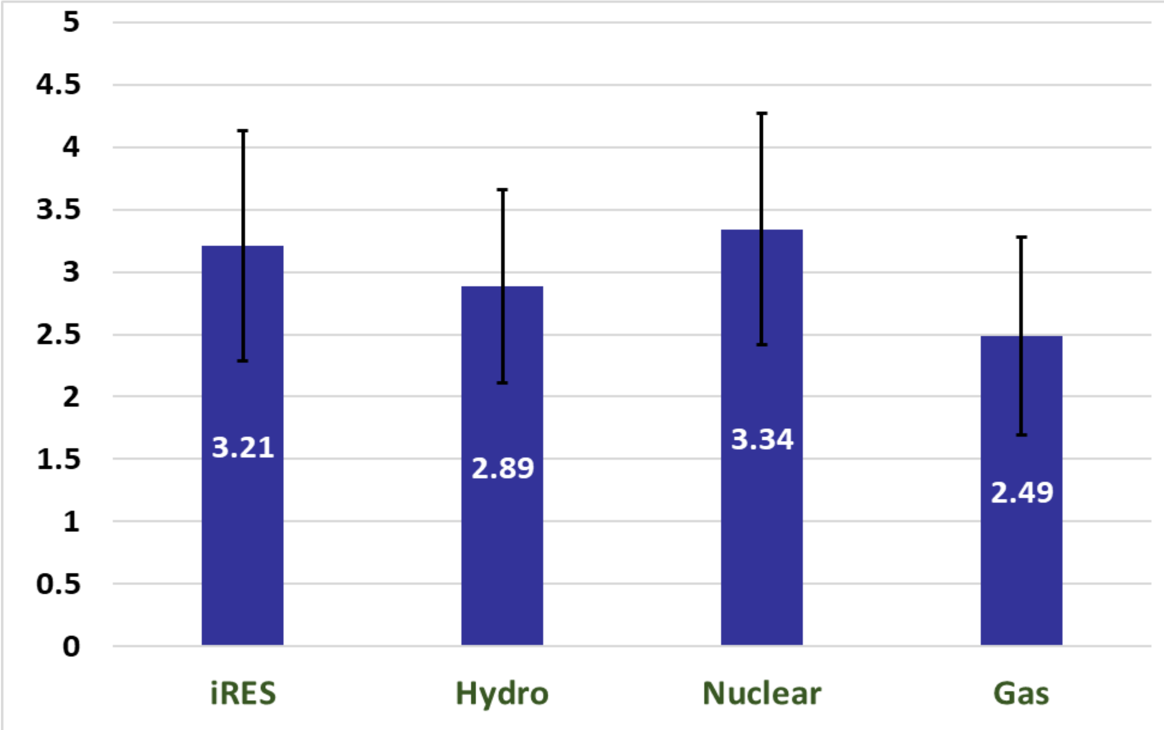


Fig. 4.3.15 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 3.13) Equality of opportunities, (S_i 3.13.1) Women's empowerment

- Hydropower (score: 2.89/5) scores 2.89, reflecting a somewhat lower contribution to women's empowerment compared to renewables and nuclear power. The hydropower industry has traditionally been male-dominated, especially in engineering and technical roles, which has resulted in fewer opportunities for women to advance within this sector. The score indicates that while there are opportunities for women in the hydropower sector, they are generally more limited compared to other energy sectors. The industry may benefit from targeted initiatives to encourage greater gender diversity, particularly in higher-level positions and technical fields.
- Natural gas (score: 2.49/5) scores 2.49, the lowest among the sectors assessed, indicating limited progress in women's empowerment. The natural gas industry, like other traditional fossil fuel sectors, has been slower to adopt gender-inclusive practices, with women often underrepresented in both technical and leadership positions. The score suggests that significant work is needed to improve gender equality in the natural gas sector. This includes creating more opportunities for women in technical roles and leadership positions, as well as addressing cultural and structural barriers that have historically limited women's participation in this industry.

These scores highlight the varying degrees of commitment and success across different energy sectors in promoting gender equality and empowering women, with traditional energy sectors generally showing lower performance compared to newer, more progressive fields like renewables.

(I 3.13) Equality of opportunities, (S_i 3.13.2) For minorities, vulnerable social groups, Indigenous peoples, children, people with disabilities

The energy sector has faced challenges related to minority equality. Historically, certain minority groups have been underrepresented in the sector, particularly in leadership positions and technical roles. However, continuous efforts have been made by all the energy technologies to promote diversity and inclusion through initiatives such as targeted recruitment, mentoring programs, and diversity training.

The assessment of sustainability performances for this indicator examines how each energy technology sector ensures equitable opportunities and addresses the specific needs of these groups within their operations and broader societal impact. Higher scores indicate *higher promotion of equal opportunity, diversity and inclusion*. The results are presented in Fig. 4.3.16.

The assessment shows that intermittent renewables (3.51) lead in promoting equality of opportunities for vulnerable groups, reflecting the sector's alignment with progressive social values and community-focused approaches. Hydropower (3.11) shows a moderate performance, with some efforts to address the needs of these groups but requiring more comprehensive policies to manage the social impacts of large-scale projects. Nuclear power (2.97) demonstrates a lower level of engagement, with a need for greater focus on the social dimensions of its operations to better support vulnerable groups. Natural gas (2.94) has the most room for improvement, highlighting the need for the sector to adopt more inclusive practices and better address the social impacts of its projects on marginalized communities.

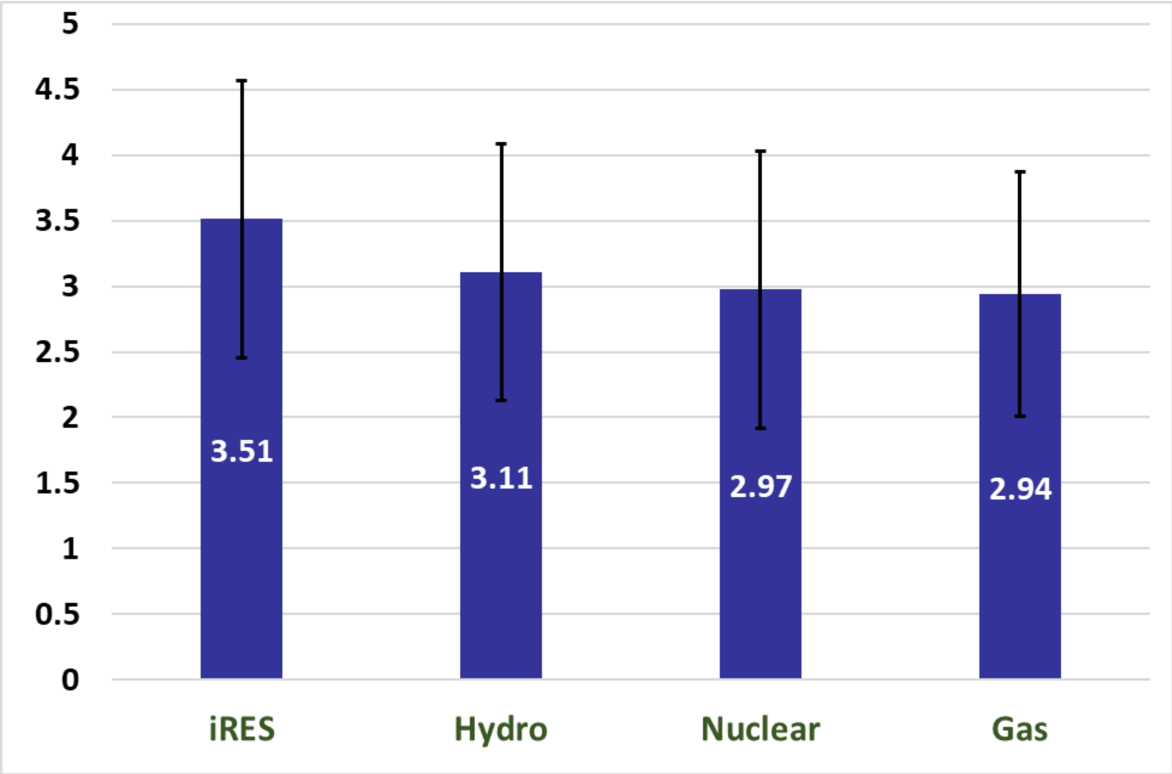


Fig. 4.3.16 Comparative assessment (iRES, Hydro, Nuclear, Gas) results for indicator (I 3.13) Equality of opportunities, (S_i 3.13.2) For minorities, vulnerable social groups, Indigenous peoples, children, people with disabilities

- Intermittent renewables (score: 3.51/5) score 3.51, indicating a relatively strong commitment to promoting equality of opportunities for minorities, vulnerable groups, Indigenous peoples, children, and people with disabilities. This sector is often linked with progressive social values, including inclusivity and community engagement, which can translate into better outcomes for these groups. The higher score reflects the sector's efforts to engage with and benefit marginalized communities, often through local projects, community ownership models, and inclusive hiring practices. However, there is still room for improvement in ensuring that these opportunities are consistently accessible across all projects and regions.
- Hydropower (score: 3.11/5) scores 3.11, reflecting a moderate level of engagement with and support for minority and vulnerable groups. The construction and operation of large hydropower projects often have significant social impacts, particularly on Indigenous peoples and local communities, which can lead to displacement and other negative effects if not properly managed. While hydropower projects can provide economic benefits to local communities, they often require more careful consideration of the social and environmental impacts on vulnerable groups. The score suggests that while some efforts are being made to address these concerns, there is a need for more robust policies and practices to ensure these groups are not disproportionately affected.
- Nuclear power (score: 2.97/5) scores 2.97, indicating a lower level of engagement with and support for minorities, vulnerable groups, and Indigenous peoples compared to renewables and hydropower. The nuclear industry has historically been less focused on the social dimensions of its impact, with more attention typically given to technical and safety concerns. The score suggests that while the nuclear industry may provide some opportunities for vulnerable groups, these are not as well developed or prioritized as in other sectors. There is potential for improvement, particularly in ensuring that the benefits of nuclear projects are more equitably distributed and that the specific needs of these groups are better addressed in the planning and implementation of projects.
- Natural gas (score: 2.94/5) scores 2.94, the lowest among the sectors assessed, indicating that this sector has the most significant challenges in promoting equality of opportunities for minorities, vulnerable groups, Indigenous peoples, children, and people with disabilities. In the opinion of the respondents, the natural gas industry has been slower to integrate inclusive practices and has often been associated with environmental and social impacts that disproportionately affect vulnerable communities. The lower score reflects the need for more proactive efforts to ensure that the benefits of natural gas projects are shared more equitably and that the negative impacts are minimized, particularly for vulnerable groups. There is a need for stronger policies and practices to address these concerns, including better community engagement, more inclusive hiring practices, and greater attention to the social impacts of natural gas development.

These scores illustrate the varying degrees of commitment and effectiveness across different energy sectors in ensuring equality of opportunities for minorities and vulnerable groups, with newer, community-oriented sectors like renewables generally performing better than traditional energy industries.

4.4 Figures of Merit, Equal Weighting

In Fig. 4.4.1 the aggregated results for the sustainability pillar "Environment" are presented for the four assessed energy technologies.

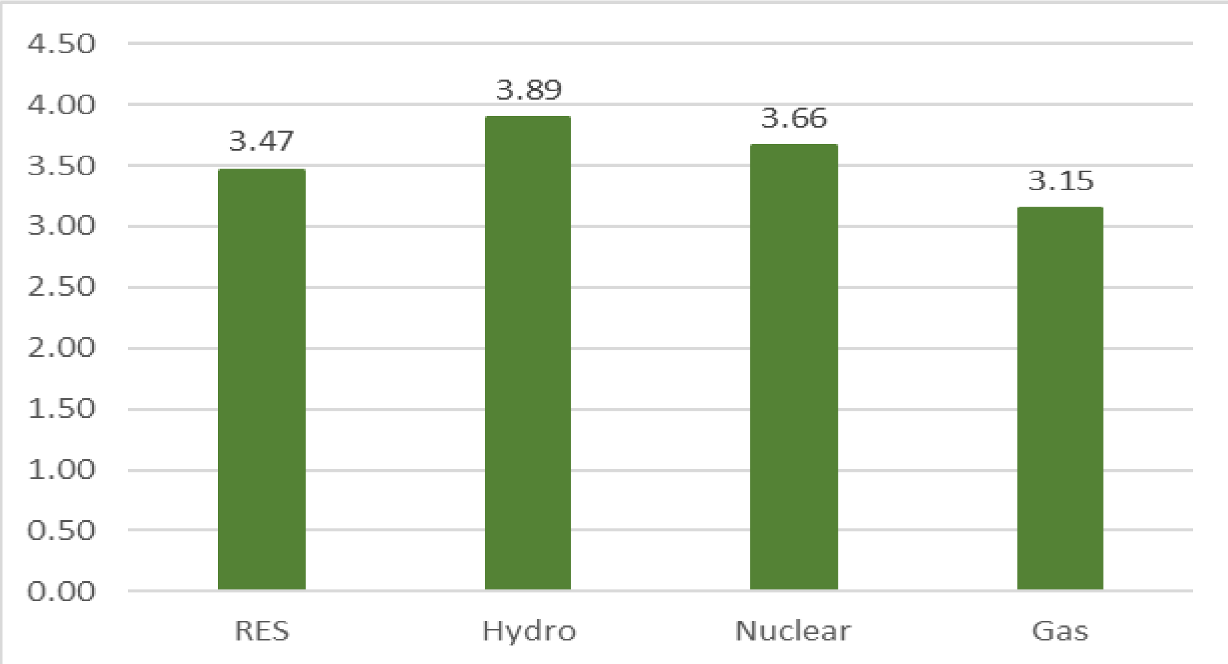


Fig. 4.4.1 Comparative assessment (iRES, Hydro, Nuclear, Gas).
Aggregated results (no-weightings) for Pillar 1 – Environment

The environmental assessment places hydropower at the top with a score of 3.89, reflecting its strong environmental performance, particularly in low emissions, though it must manage ecological impacts. Nuclear power follows with a score of 3.66, balancing low operational emissions with challenges in waste management. Intermittent renewables score 3.47, underscoring their importance in emissions reduction, but with considerations around lifecycle impacts like material use and land requirements. Natural gas scores the lowest at 3.15, indicating its role as a cleaner fossil fuel but with significant environmental concerns, particularly around methane emissions

- Hydropower (Score: 3.89/5) achieves the highest environmental score at 3.89, indicating strong environmental performance. This high score reflects the renewable nature of hydroelectricity, which generates low greenhouse gas emissions during operation. Additionally, hydropower has a relatively small carbon footprint over its lifecycle compared to fossil fuels. While hydropower performs well environmentally, it's important to consider the potential ecological impacts, such as habitat disruption, fish migration issues, and changes to local water ecosystems. However, the benefits of clean energy production and long operational lifespans contribute to its strong environmental performance.
- Nuclear power (Score: 3.66/5) scores 3.66, indicating robust environmental performance, particularly in terms of low carbon emissions during operation. Nuclear energy is a low-carbon energy source that contributes significantly to reducing greenhouse gas emissions. However, its environmental score is tempered by concerns related to radioactive waste management, potential for catastrophic events, and long-term environmental impacts. The relatively high score reflects

the balance between nuclear power's low operational emissions and the environmental challenges associated with waste disposal and decommissioning. Effective management of these challenges is crucial for maintaining and potentially improving nuclear power's environmental sustainability.

- Intermittent renewables (Score: 3.47/5) score 3.47, reflecting their significant environmental benefits, particularly in terms of emissions reduction. These technologies have minimal operational emissions and are vital in the global shift towards a sustainable energy system. However, the environmental score is influenced by factors such as land use, resource extraction for materials, and the recyclability of components like solar panels and wind turbine blades. The score highlights the strong environmental credentials of renewables, while also acknowledging the challenges associated with their lifecycle impacts. Ongoing improvements in material efficiency, recycling, and sustainable land management can enhance their overall environmental performance.

- Natural gas (Score: 3.15/5) scores 3.15, indicating moderate environmental performance. While natural gas is cleaner than coal and oil, emitting less CO2 per unit of energy produced, it is still a fossil fuel with associated environmental concerns, including methane leakage, which is a potent greenhouse gas. The environmental impact of natural gas extraction, particularly from unconventional sources like shale gas, also contributes to its lower score. The moderate score reflects the dual nature of natural gas as a relatively cleaner fossil fuel but still a significant source of greenhouse gas emissions. Its role as a bridge fuel in the transition to a low-carbon economy is acknowledged, but its environmental limitations underscore the need for further innovation in emission reduction technologies and potential replacements by renewables.

These results highlight the diverse environmental profiles of different energy technologies and the importance of considering a full range of environmental factors, from emissions to resource use, in assessing sustainability.

In Fig. 4.4.2 the aggregated results for the pillar "Economics" are presented for the four analyzed energy technologies.

The economic sustainability assessment highlights that nuclear power leads with the highest score of 3.60, indicating strong long-term economic benefits despite high initial costs. Natural gas follows closely with a score of 3.50, reflecting its economic attractiveness due to low capital costs and operational flexibility, though it faces future challenges related to price volatility and carbon regulation. Hydropower scores 3.35, balancing low operational costs and long lifespans against high upfront investment. Intermittent renewables score the lowest at 3.01, reflecting ongoing economic challenges related to grid integration and intermittency, though their economic outlook is improving with technological advancements and policy support.

The sustainability assessment for the pillar Economics, which aggregates all relevant indicators and sub-indicators, reveals the following scores on a scale from 1 to 5:

- Nuclear power (Score: 3.60/5) achieves the highest economic sustainability score at 3.60. This indicates a relatively strong economic performance, likely reflecting the long-term cost stability, low fuel costs, and the potential for large-scale electricity generation that nuclear power offers. Despite high upfront capital costs and long construction times, the economic benefits of nuclear power include extended plant lifetimes and low operational costs once the plants are established. The result underscores nuclear power's ability to contribute significantly to a stable and economically sustainable energy mix. However, this must be balanced against the risks of cost overruns, long-term waste management, and decommissioning costs, which continue to pose economic challenges.

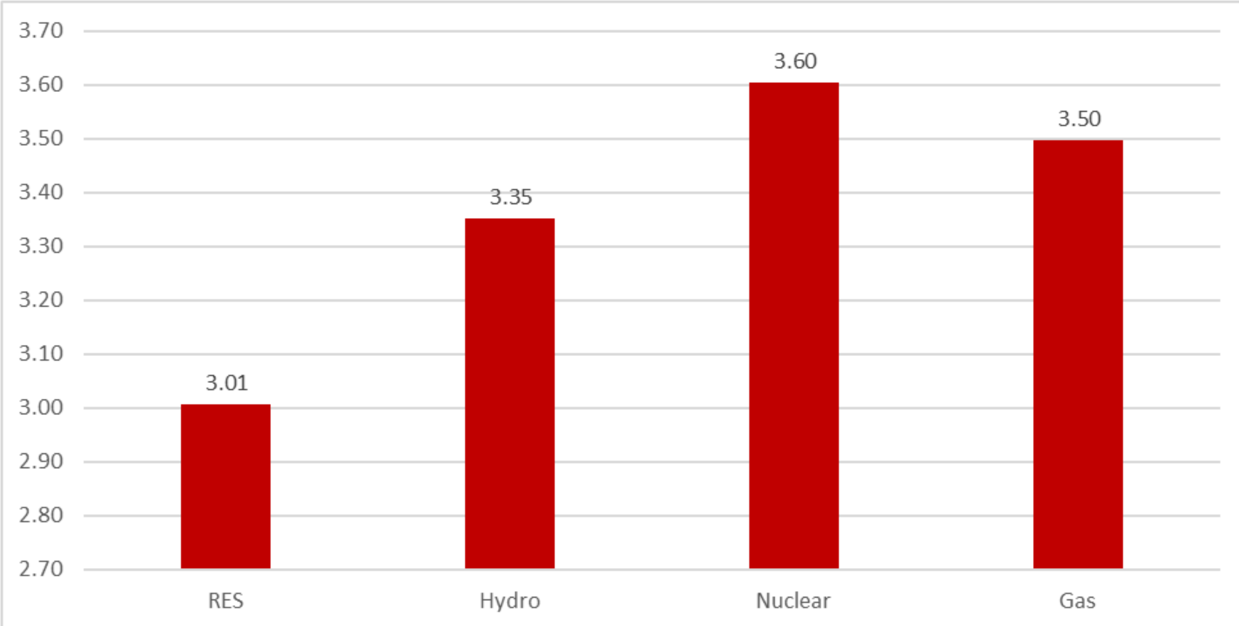


Fig. 4.4.2 Comparative assessment (iRES, Hydro, Nuclear, Gas).
Aggregated results (no-weightings) for Pillar 2 – Economics

- Natural gas (Score: 3.50/5) gas closely follows with a score of 3.50, reflecting its strong economic performance. Natural gas is often favored for its relatively low initial capital investment, quick ramp-up times, and the flexibility it offers in electricity generation. It is also supported by established infrastructure and supply chains, which contribute to its economic appeal. The score suggests that natural gas remains a competitive option economically, particularly for its role in providing a flexible and reliable energy source. However, the volatility of natural gas prices and concerns over future carbon pricing could impact its long-term economic viability.
- Hydropower (Score: 3.35/5) scores 3.35, reflecting a solid economic performance, though slightly lower than nuclear and natural gas. Hydropower benefits from very low operational costs and long asset lifespans, which make it an economically attractive option. However, the economic score is tempered by the high capital costs associated with dam construction and the potential environmental and social costs that can affect project viability. The score indicates that while hydropower is economically sustainable, the financial feasibility of new projects can be challenged by upfront costs and regulatory hurdles. The economic benefits are more pronounced in regions where the necessary infrastructure already exists or where large-scale projects are feasible.
- Intermittent renewables (Score: 3.01/5) have the lowest economic sustainability score at 3.01. This reflects the challenges associated with their economic performance, including the intermittency of energy supply, the need for backup systems or storage, and the relatively high costs of integration into existing grids. However, declining costs of renewable technologies and increasing efficiency are gradually improving their economic competitiveness. The lower score suggests that while renewables are becoming more economically viable, they still face challenges in terms of economic sustainability compared to more established energy sources. Continued advancements in technology, coupled with supportive policies and market mechanisms, are essential to improving the economic performance of renewables over time.

These scores suggest that while nuclear and natural gas currently offer the strongest economic performance, hydropower and intermittent renewables are also important components of a balanced and sustainable energy mix, each with its own economic strengths and challenges.

In Fig. 4.4.3 the aggregated results for the pillar "Social" are presented for the four analyzed energy technologies.

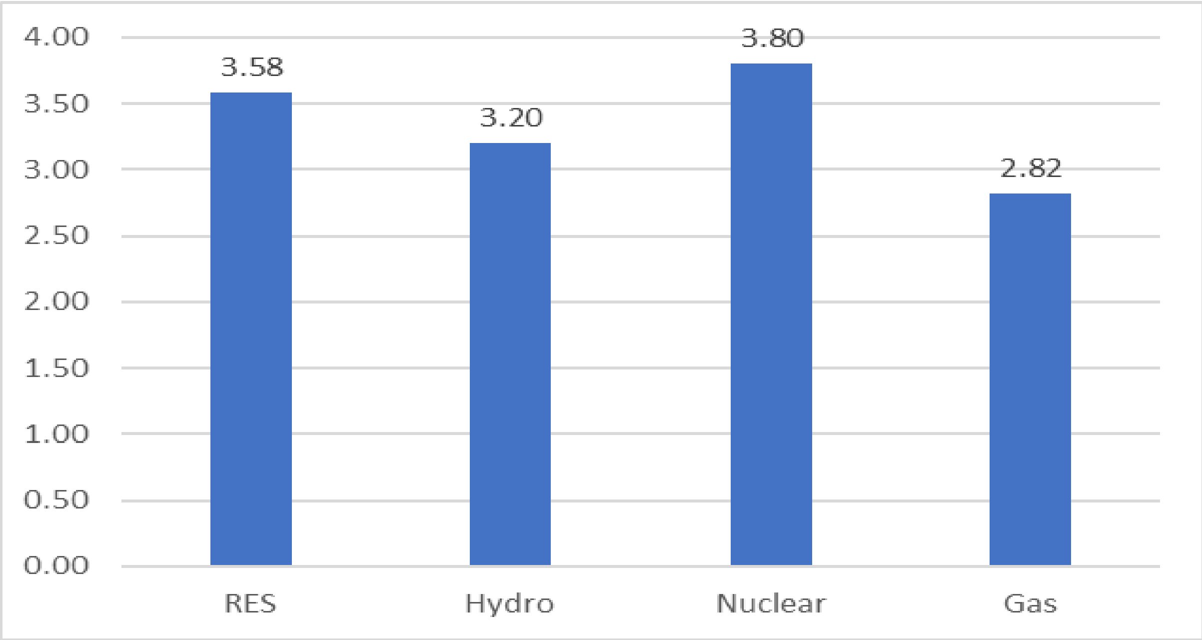


Fig. 4.4.3 Comparative assessment (iRES, Hydro, Nuclear, Gas).
Aggregated results (no-weightings) for Pillar 3 – Social

The social sustainability assessment reveals that nuclear power leads with the highest score of 3.80, reflecting its strong emphasis on safety, job creation, and community benefits. Intermittent renewables follow closely with a score of 3.58, highlighting their positive social impacts through clean energy promotion, job creation, and local engagement. Hydropower scores 3.20, showing a moderate social performance that balances significant benefits with potential social and environmental challenges. Natural gas scores the lowest at 2.82, indicating considerable social concerns, particularly related to health risks, environmental justice, and the long-term impacts of fossil fuel reliance.

- Nuclear power (Score: 3.80/5) achieves the highest score in social sustainability at 3.80. This reflects the sector's significant focus on safety, security, and the well-being of both workers and surrounding communities. The nuclear industry is known for its stringent safety standards, extensive regulatory oversight, and the creation of highly skilled jobs, which contribute to social stability. Additionally, the long-term employment opportunities and investments in local communities associated with nuclear facilities further enhance its social score. The high social sustainability score indicates that nuclear power is generally perceived as a socially responsible energy source, particularly in terms of safety and community impact. However, public concerns about nuclear accidents, waste management, and the long-term risks associated with radioactive materials remain challenges that need continuous attention to maintain social acceptance.

- Intermittent Renewables (Score: 3.58/5) reflecting strong social sustainability performance. These technologies are often associated with positive social impacts, such as the promotion of clean energy, reduction of pollution, and the creation of jobs in emerging sectors. Renewables also offer the potential for community ownership models and decentralized energy production, which can enhance social equity and local engagement. The score highlights the social benefits of renewables, including their role in advancing environmental justice and reducing health risks associated with fossil fuels. However, challenges such as the visual impact of wind turbines, land use conflicts, and the need for a just transition for workers in traditional energy sectors must be managed to sustain and improve this social performance.

- Hydropower (Score: 3.20/5) scores 3.20 in social sustainability, reflecting a moderate performance. While hydropower projects can provide significant social benefits, such as reliable energy supply and flood control, they can also pose social challenges. These include the displacement of communities, impacts on local ecosystems, and conflicts over water use. The social impact of hydropower is often highly context-dependent, varying significantly based on the scale of the project and the measures taken to mitigate negative effects. The score suggests that while hydropower has important social benefits, it also requires careful management to address the potential social and environmental trade-offs. Successful hydropower projects often depend on effective community engagement and equitable distribution of benefits to ensure positive social outcomes.
- Natural Gas (Score: 2.82/5) has the lowest score in social sustainability at 2.82. This lower score reflects concerns about the social impacts of natural gas extraction and use, including issues such as air and water pollution, health risks for nearby communities, and the social costs of fossil fuel dependence. Additionally, the potential for job losses in the transition to a low-carbon economy and the unequal distribution of benefits and burdens associated with natural gas projects contribute to its lower social score. The score indicates significant social challenges associated with natural gas, particularly in terms of health impacts and environmental justice. As the energy transition progresses, there will be an increasing need to address these social concerns, potentially through policies that support affected communities and workers in transitioning to more sustainable industries.

These results suggest that while nuclear power and intermittent renewables perform well in terms of social sustainability, hydropower requires careful management to address its social impacts, and natural gas faces the most significant social challenges, particularly in the context of the ongoing energy transition.

In Fig. 4.4.4 the aggregated results for Overall Sustainability Performance are presented, considering the four analyzed energy technologies.

The overall sustainability assessment places nuclear power at the top with a score of 3.68, highlighting its strong balance across environmental, economic, and social dimensions, albeit with some challenges in waste management and public perception. Hydropower follows closely with a score of 3.56, reflecting its well-rounded sustainability profile, though site-specific social and ecological impacts must be managed. Intermittent renewables score 3.37, showing strong environmental benefits but facing economic and resource management challenges. Natural gas scores the lowest at 3.16, indicating moderate sustainability due to its mixed environmental performance and ongoing social concerns.

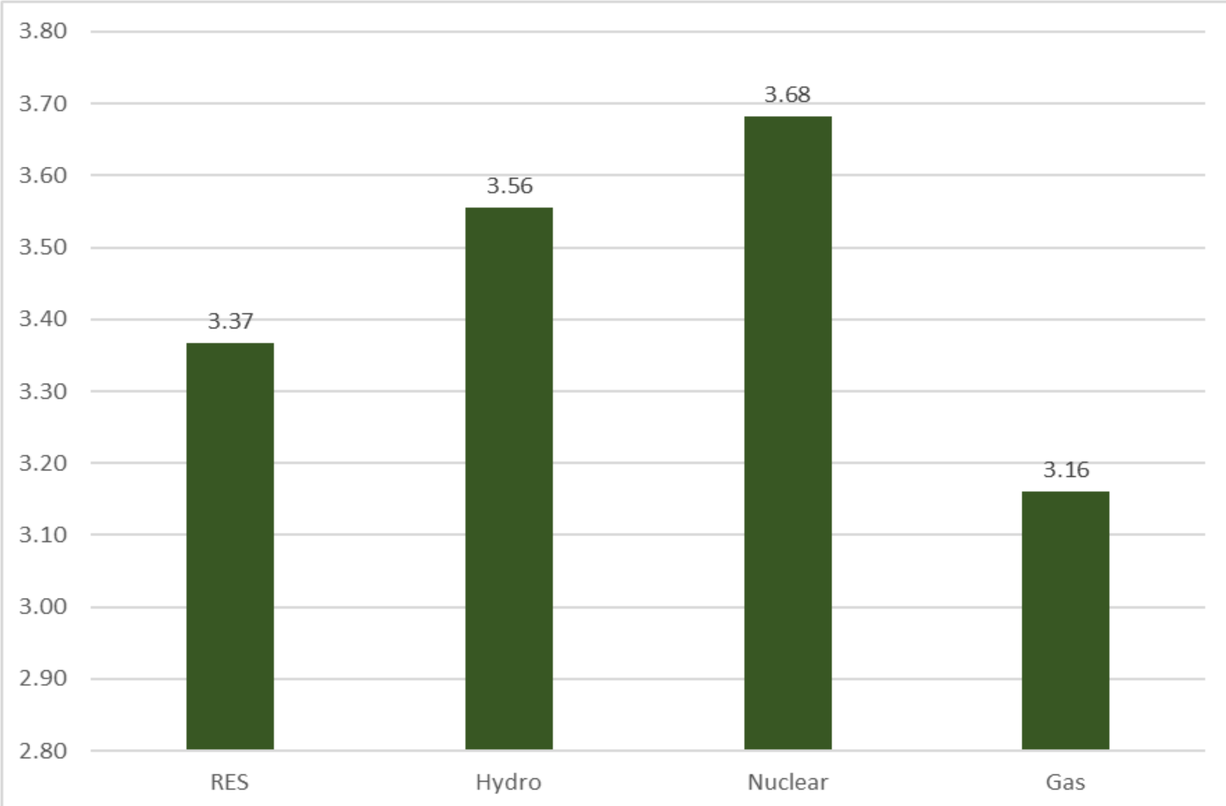


Fig. 4.4.4 Comparative assessment (iRES, Hydro, Nuclear, Gas).
Global aggregated results (no-weightings). Figures of Merit

- Nuclear power (Score: 3.68/5) achieves the highest overall sustainability score at 3.68. This score reflects a balance of strong environmental performance due to low operational carbon emissions, robust economic factors such as reliability and long-term cost stability, and a generally positive social performance, though tempered by concerns related to safety, radioactive waste, and public perception. The high score indicates that nuclear power is viewed as a sustainable option, particularly for countries seeking to reduce carbon emissions while ensuring a stable energy supply. However, ongoing challenges in waste management and public acceptance must be addressed to maintain and enhance its sustainability profile.
- Hydropower (Score: 3.56/5) follows closely with a score of 3.56, reflecting strong sustainability across all three pillars. Environmentally, hydropower is a low-emission, renewable energy source with significant economic benefits, including long operational lifespans and low operating costs. Socially, it tends to have a positive impact, although it can raise concerns related to ecosystem disruption and displacement of local communities. Hydropower's strong score highlights its role as a cornerstone of sustainable energy in many regions. The balance of low emissions, economic viability, and social considerations make it a highly sustainable option, although site-specific impacts on ecosystems and communities require careful management.
- Intermittent renewables (Score: 3.37/5) score 3.37, reflecting their growing importance in the sustainable energy landscape. These technologies have minimal environmental impact in terms of emissions, though they face economic challenges related to intermittency and the need for storage solutions. Socially, renewables generally receive positive support, though land use and resource extraction for materials can be contentious. The score shows the significant potential of wind and

solar power in contributing to a sustainable energy future. While they offer strong environmental benefits, the challenges associated with economic stability and resource management need ongoing attention to improve their overall sustainability.

- Natural gas (Score: 3.16/5) scores the lowest at 3.16, indicating moderate sustainability performance. While it has economic advantages, such as being relatively cost-effective and providing stable energy, it is less favorable environmentally due to its status as a fossil fuel, and socially, it faces challenges related to emissions and public perception, particularly concerning methane leaks and air quality impacts. The moderate score reflects the transitional role of natural gas in the energy mix. While it is cleaner than other fossil fuels and provides economic stability, its environmental and social drawbacks limit its overall sustainability. Future improvements in emission controls and the gradual shift towards cleaner energy sources are necessary to enhance its sustainability profile.

These scores highlight the complexities of assessing sustainability across multiple dimensions, emphasizing that while respondents judge that all these technologies could have roles to play in a sustainable energy future, each comes with its unique set of strengths and challenges.

4.5 Figures of Merit, Differential Weights

During the ECOSENS International Stakeholder Workshop of March 2023, an exercise was dedicated to gathering input from the stakeholders regarding the relative importance (weight) to be assigned to various indicators. The developers of the methodology consider that stakeholders can provide insights based on their expertise and diversified perspectives on the energy system. The workshop participants were invited to attribute weights as an expression of their views on the prioritization of the pillars, sub-indicators and indicators. The averaged values are presented in Table 4.5.1, and denoted as set 1 (S1). In this case no weights for sub-indicators nor for the overall pillars were obtained. Unfortunately, the weighting was a real challenge for many of the participants: some mentioned a perception of personal insufficient knowledge, others the short time allotted to the exercise. However, a detailed discussion furthermore exposed the point of view that it may not be the role of a limited set of societal stakeholders to generate the weights. The discussion considered whether this should be the prerogative of policy makers, or alternatively, the outcome of a carefully designed, equitable democratic process. In either case, it was argued, the assessed sustainability impacts of each energy technology would have to be conveyed in a detailed but workable form to those tasked with weighting [3].

Table 4.5.1 Set (S1) of weightings, International Stakeholder Workshop [2]

		Stakeholders (average value of 6 participants) [%]
En-LCA	1.1 Carbon emissions	15.1
	1.2 Land occupation and power density	8.9
	1.3 Energy returned on investment	8.4
	1.4 Impact on resources	12.2
	1.5 Potential material recyclability	8.4
	1.6 Emissions (other than C - Carbon)	8.4
	1.7 Impact on life and ecosystems (under normal operation)	10.8
	1.8 Impact of generated wastes	10.1
	1.9 Impact of accidental situations	9.7
	1.10 Mitigation of accidents	8
Eco-LCA	2.1 Capacity factor	7
	2.2 Global efficiency	9
	2.3 Cost	18
	2.4 Cost for system integration	18
	2.5 External costs	9
	2.6 LCOE	10
	2.7 Macro-economic impact	14
	2.8 Applicability for cogeneration	7
	2.9 Level of standards generated, rules and control	8

Soc-LCA	3.1 Jobs created	11.6
	3.2 Impact on the local/regional business (partner with other business)	16.7
	3.3 Additional goods and services created	6.3
	3.4 Value of the knowledge generated and maintained for the future	5
	3.5 Impact on education	6.7
	3.6 Contribute to the reduction of inherited burdens (toxic wastes, military stocks)	4
	3.7 Impact on health improvement	11.7
	3.8 Impact on poverty	10
	3.9 Societal-level adoption of the technology	4.3
	3.10 Existing investment in RDI to develop the technology	4.3
	3.11 Dependency on government support (funding or incentives, such as tax credits or subsidies)	5
	3.12 Risks	8.7
	3.13 Equality of opportunities	5.7

In the second weighting process, 26 technical experts from RATEN ICN introduced their perception on the relative importance of the 62 indicators, sub-indicators, and pillars. The averaged values are presented in Table 4.5.2.

Table 4.5.2 Set of weightings, W1 (pillars), W2 (indicators), W3 (Sub-indicators)

	Indicators	W1 [%]	W2 [%]	W3 [%]
Environment				
1.1	Carbon emissions	36.19	10.45	
1.2	Land occupation		8.61	
1.3	Energy returned on investment		9.53	
1.4.1	Operational water consumption		9.53	19.90
1.4.2	Abiotic resources depletion			18.68
1.4.3	Depletion of fossil fuels			19.39
1.4.4	Excessive use of resources useful for the life sustaining			22.03
1.4.5	Exhausting of rare resources			20.00
1.5	Potential material recyclability		9.72	
1.6.1	Emissions (other than C) - NOx and SO2 emissions		9.80	25.80
1.6.2	Emissions (other than C) - Ozone depletion potential			25.56
1.6.3	Emissions (other than C) - Photochemical oxidant creation potential			24.20
1.6.4	Emissions (other than C) - Cumulative lifecycle emissions of NMVOC and PM2.5			24.44

1.7.1	Impact on life and ecosystems (under normal operation) - Human toxicity potential		10.36	14.88
1.7.2	Impact on life and ecosystems (under normal operation) - Human health/mortality impact			15.08%
1.7.3	Impact on life and ecosystems (under normal operation) - Ecotoxicity			13.94
1.7.4	Impact on life and ecosystems (under normal operation) - Acidification and eutrophication potential			13.28
1.7.5	Impact on life and ecosystems (under normal operation)- Freshwater ecotoxicity			14.94
1.7.6	Impact on life and ecosystems (under normal operation)- Marine ecotoxicity			13.81
1.7.7	Impact on life and ecosystems (under normal operation)- Biodiversity of the used land			14.08
1.8.1	Impact of generated wastes - Chemical (generated) waste volumes		10.24	23.14
1.8.2	Impact of generated wastes - Radioactive wastes (generated)			25.97
1.8.3	Impact of generated wastes - Maturity of the approach (experience and effectivity in waste management)			24.91
1.8.4	Impact of generated wastes - Long-term effect of deposited wastes			25.97
1.9.1	Impact of accidental situations - Impact of the accidents (anticipated, design base)		10.86	50.33
1.9.2	Impact of accidental situations - Impact of severe accidents (considering mitigation/prevention…)			49.67
1.10.1	Mitigation of accidents - Inherent safety		10.89	33.63
1.10.2	Mitigation of accidents - Passive systems			31.70
1.10.3	Mitigation of accidents - Safety by design			34.67
			100.00	
	Economics			
2.1	Capacity factor	30.49	11.04	
2.2	Global efficiency		11.36	
2.3.1	Cost - Cost of the investment (capital cost)		12.17	33.92
2.3.2	Cost - Cost of operation (including fueling and maintenance)			33.04
2.3.3	Cost - Cost of decommissioning (including environmental remediation)			33.04
2.4.1	Cost for system integration – Maneuverability		11.80	18.92
2.4.2	Cost for system integration – Load following			19.78
2.4.3	Cost for system integration – Stability			21.73
2.4.4	Cost for system integration – Easy to be integrated in local/regional grids			19.46
2.4.5	Cost for system integration – Realistic solution for large scale storage			20.11
2.5	External costs		10.21	

2.6	LCOE †		9.44	
2.7	Macro-economic impact		11.93	
2.8	Applicability for cogeneration		10.53	
2.9.1	Level of standards generated, rules and control - Maturity of the authorization process			34.13
2.9.2	Level of standards generated, rules and control - Level of industrial codes and standards		11.53	32.66
2.9.3	Level of standards generated, rules and control - Needs for technical support			33.21
			100.00	
Social				
3.1.1	Jobs created - Direct high-education jobs		8.10	51.37
3.1.2	Jobs created - Jobs in contributing industries			48.63
3.2	Impact on the local/regional business (partner with other business)		7.36	
3.3	Additional goods and services created		7.07	
3.4	Value of the knowledge generated and maintained for the future		7.80	
3.5	Impact on education		8.32	
3.6	Contribute to the reduction of inherited burdens (toxic wastes, military stocks)		8.08	
3.7	Impact on health improvement	33.32	8.97	
3.8	Impact on poverty		8.24	
3.9	Social level adoption of the technology		6.87	
3.10	Existing investment in RDI to develop the technology		7.88	
3.11	Dependency on government support (funding/ incentives, such as tax credits or subsidies)		6.91	
3.12.1	Risks - Level of risk reflected in insurance needs		7.31	47.79
3.12.2	Risks - Proliferation of sensitive materials			52.21
3.13.1	Equality of opportunities - Women's empowerment		7.07	50.29
3.13.2	Equality of opportunities - For minorities, vulnerable social groups, Indigenous peoples, children, people with disabilities			49.71

The two sets of weightings were applied sequentially to the results obtained on each indicator (sections 4.1, 4.2, 4.3). The use of the two set of weights to produce the aggregated scores may be seen as a sensitivity calculation (Table 4.5.3) offering an idea about the influences of the weighting.

The application of these weights resulted in new figures of merit for the three pillars (Environment, Economics, and Social). The figures are presented in Fig. 4.5.1 (Environment), Fig. 4.5.2 (Economics), 4.5.3 (Social), comparing in each case the figure of merit obtained by application respectively of S1 and S2 sets of weights.

The global (all-pillars) figures of merit for each energy source's sustainability performance are presented comparatively in Fig. 4.5.4.

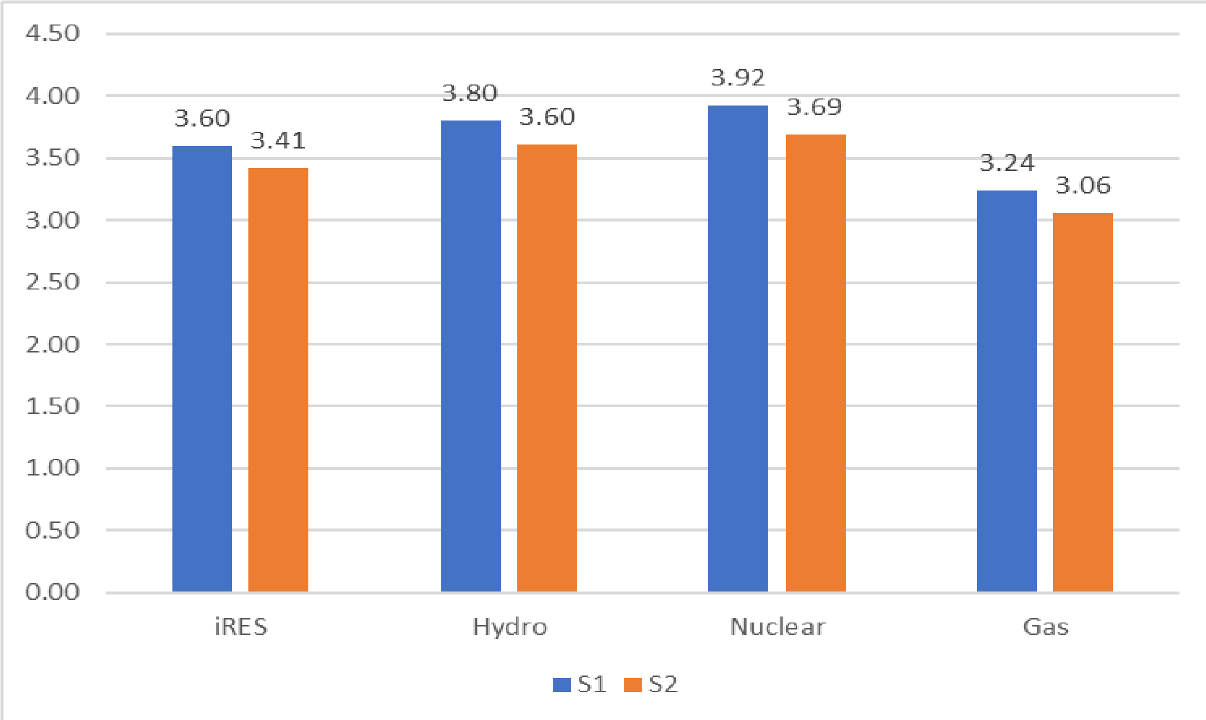


Fig. 4.5.1 Comparative assessment (iRES, Hydro, Nuclear, Gas).
Figures of merit for Pillar 1 – Environment according to weighting provided by diverse (S1) and technical (S2) stakeholders.

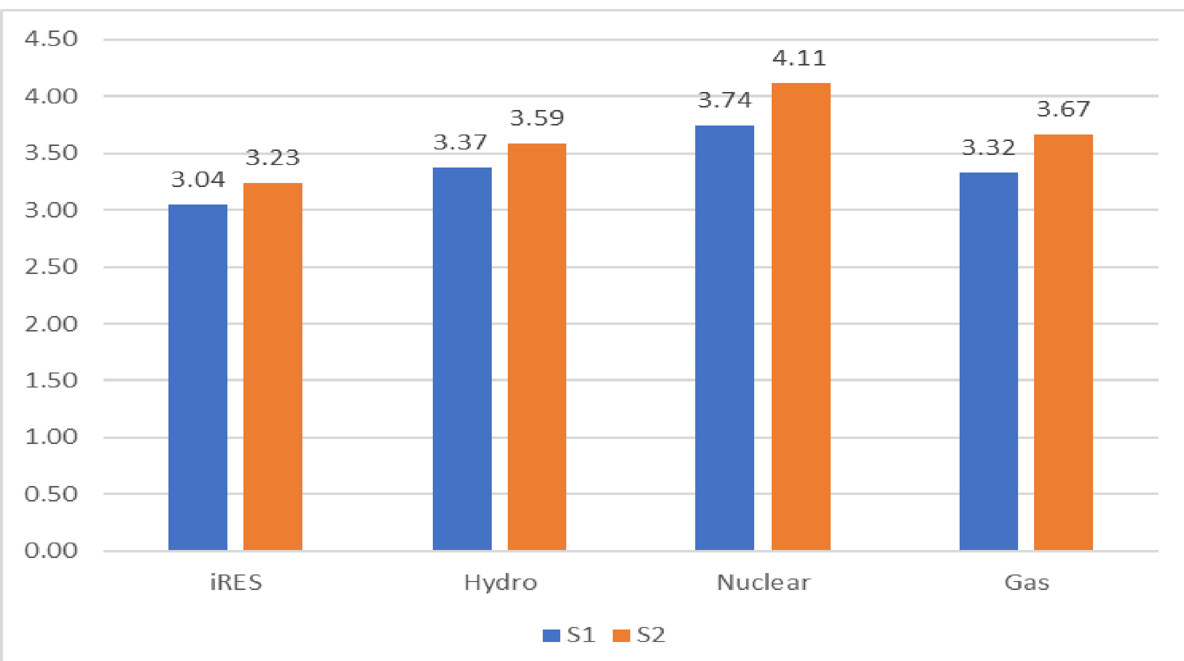


Fig. 4.5.2 Comparative assessment (iRES, Hydro, Nuclear, Gas).
Figures of merit for Pillar 2 – Economic according to weighting provided by diverse (S1) and technical (S2) stakeholders.

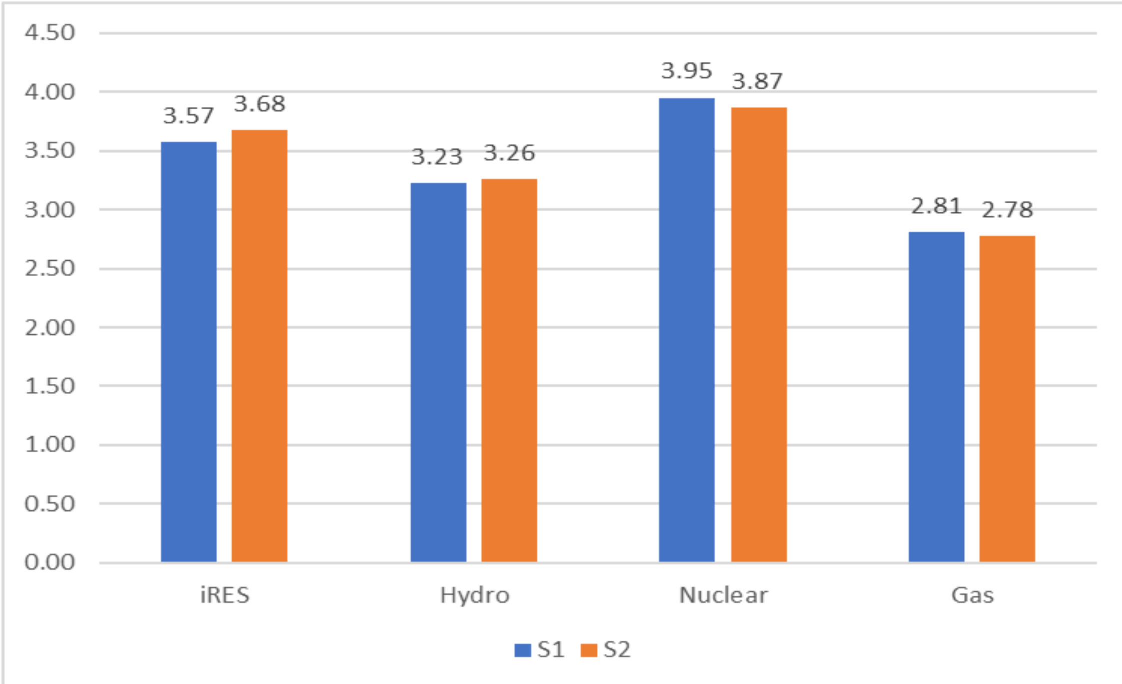


Fig. 4.5.3 Comparative assessment (iRES, Hydro, Nuclear, Gas).
Figures of merit for Pillar 3 – Social according to weighting provided by diverse (S1) and technical (S2) stakeholders

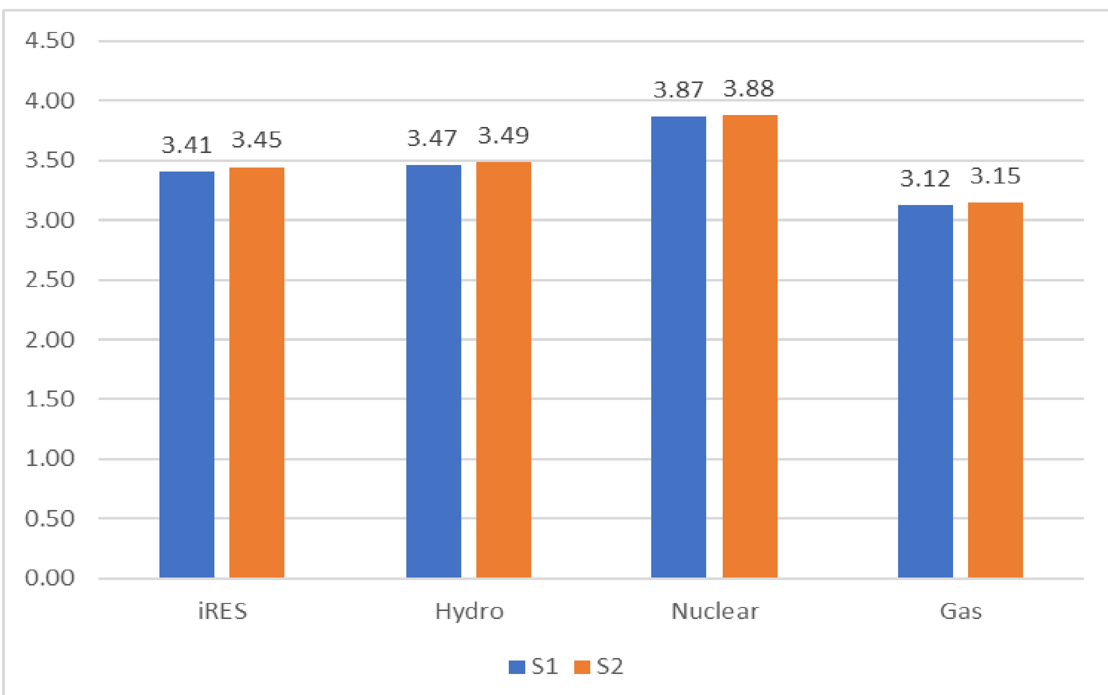


Fig. 4.5.4 Comparative assessment (iRES, Hydro, Nuclear, Gas).
Global Figure of Merit, all sustainability pillars, according to weighting provided by diverse (S1) and technical (S2) stakeholders.

Table 4.5.3 Comparison of energy sources sustainability Figures of Merit according to weights S1 and S2

Pillar	Set of weightings	iRES	Hydro	Nuclear	Gas
Environment	S1	3.60	3.80	3.92	3.24
	S2	3.41	3.60	3.69	3.06
	S2 vs S1	-5%	-5%	-6%	-6%
Economics	S1	3.04	3.37	3.74	3.32
	S2	3.23	3.59	4.11	3.67
	S2 vs S1	6%	6%	10%	10%
Social	S1	3.57	3.23	3.95	2.81
	S2	3.68	3.26	3.87	2.78
	S2 vs S1	3%	1%	-2%	-1%
Overall Sustainability Performance	S1	3.41	3.47	3.87	3.12
	S2	3.45	3.49	3.88	3.15
	S2 vs S1	1%	1%	0%	1%

5 Considerations for the role of nuclear power

5.1 Analytic summary of nuclear power's strongest and weakest performances

In Table 5.1 the scores obtained for nuclear power on all the 62 indicators and sub-indicators are presented, with a focus on the position achieved in the assessed sustainability performance. In the last column of the table, the score is expressed as percentage of the maximum performance (with a score of "5" ranking therefore as 100%).

Nuclear power was appraised as the best sustainability performer among all assessed energy technologies as follows:

- 7 indicators/sub-indicators (out of a possible 29) for the Environment pillar: Carbon emissions, Land occupation, Cumulative lifecycle emissions of NMVOC and PM2.5, Biodiversity of the used land, Impact of the accidents (anticipated, design base), Passive systems, Safety by design.
- 6 indicators/sub-indicators (out of a possible 17) for the Economics pillar: Capacity factor, Global efficiency, Cost for system integration – Stability, Realistic solution for large scale storage, LCOE, Macro-economic impact.
- 9 indicators/sub-indicators (out of a possible 16) for the Social pillar: Direct high-education jobs, Jobs in contributing industries, Impact on the local/regional business (partner with other business), Additional goods and services created, Value of the knowledge generated and maintained for the future, Impact on education, Contribute to the reduction of inherited burdens (toxic wastes, military stocks), Non-proliferation of sensitive materials, Equality of opportunities - Women's empowerment.

Nuclear energy obtained the second position for 12 indicators/sub-indicators of Environmental pillar, 5 for Economics, and 4 for Social.

In terms of the perceptions of the drawbacks of nuclear, the lowest sustainability performances were appraised for:

- 5 indicators/sub-indicators for the Environmental pillar: Potential material recyclability, Marine ecotoxicity, Radioactive wastes (generated), Long-term effect of deposited wastes, Impact of severe accidents.
- 3 indicators/sub-indicators for the Economics pillar: Maneuverability, Load following, Needs for technical support.
- 2 indicators/sub-indicators for the Social pillar: Social level adoption of the technology, Level of risk reflected in insurance needs.

It must be kept in mind that ratings of the sustainability of nuclear power technology displayed a noticeable degree of (comparative) dissensus on several indicators. These included inter alia:

- 5 indicators/sub-indicators for the Environment pillar: Non-carbon emissions (NOx & SO_2 and NMVOC & PM2.5; both these sub-indicators displayed dissensus across technologies); Impact of severe accidents; Ozone depletion potential; Photochemical oxidant creation potential
- 3 indicators/sub-indicators for the Economics pillar: Capital cost; Levelized cost of electricity (LCOE); Cost of decommissioning (including environmental remediation)

- 3 indicators/sub-indicators for the Social pillar: Dependency on government support; Level of risk reflected in insurance needs; Proliferation of sensitive materials.

These indicators are marked with a dagger (†) in Table 5.1, because the obtained mean score may translate a range of differential knowledge, awareness, sensitivity, and/or evaluative opinion, which it would be meaningful to discuss with stakeholders in view of understanding the potential role of nuclear power in the energy transition.

Table 5.1 Scores for Nuclear power sustainability performance (scale 1 to 5)

		Relative position in performance	**Score**	**Score / maximum (%)**
Environmental Life Cycle Assessment (En-LCA)				
1.1	Carbon emissions	1	4.69	93.8%
1.2	Land occupation	1	4.61	92.2%
1.3	Energy returned on investment	2	3.82	76.4%
1.4.1	Operational water consumption	2	3.62	72.4%
1.4.2	Abiotic resources depletion	2	4.00	80.0%
1.4.3	Depletion of fossil fuels	3	3.23	64.6%
1.4.4	Excessive use of resources useful for the life sustaining	2	3.45	69.0%
1.4.5	Exhausting of rare resources	2	3.62	72.4%
1.5	Potential material recyclability	4	2.96	59.2%
1.6.1	Emissions (other than C) - NOx and SO2 emissions †	2	3.98	79.6%
1.6.2	Emissions (other than C) - Ozone depletion potential†	3	3.11	62.2%
1.6.3	Emissions (other than C) - Photochemical oxidant creation potential†	2	3.50	70.0%
1.6.4	Emissions (other than C) - Cumulative lifecycle emissions of NMVOC and PM2.5 †	1	3.75	75.0%
1.7.1	Impact on life and ecosystems (under normal operation)- Human toxicity potential	2	3.38	67.6%
1.7.2	Impact on life and ecosystems (under normal operation)- Human health/mortality impact	3	2.90	58.0%
1.7.3	Impact on life and ecosystems (under normal operation)- Ecotoxicity	2	3.23	64.6%

1.7.4	Impact on life and ecosystems (under normal operation)- Acidification and eutrophication potential	2	3.54	70.8%
1.7.5	Impact on life and ecosystems (under normal operation)- Freshwater ecotoxicity	3	2.90	58.0%
1.7.6	Impact on life and ecosystems (under normal operation)- Marine ecotoxicity	4	2.69	53.8%
1.7.7	Impact on life and ecosystems (under normal operation)- Biodiversity of the used land	1	3.85	77.0%
1.8.1	Impact of generated wastes - Chemical (generated) waste volumes	2	3.53	70.6%
1.8.2	Impact of generated wastes - Radioactive wastes (generated)	4	2.66	53.2%
1.8.3	Impact of generated wastes - Maturity of the approach (experience and effectivity in waste management)	3	4.21	84.2%
1.8.4	Impact of generated wastes - Long-term effect of deposited wastes	4	2.74	54.8%
1.9.1	Impact of accidental situations - Impact of the accidents (anticipated, design base)	1	3.43	68.6%
1.9.2	Impact of accidental situations - Impact of severe accidents (considering mitigation/prevention…) †	4	2.81	56.2%
1.10.1	Mitigation of accidents - Inherent safety	2	3.86	77.2%
1.10.2	Mitigation of accidents - Passive systems	1	4.08	81.6%
1.10.3	Mitigation of accidents - Safety by design	1	4.41	88.2%
Economic Life Cycle Assessment (Ec-LCA)				
2.1	Capacity factor	1	4.82	96.4%
2.2	Global efficiency	1	4.00	80.0%
2.3.1	Cost - Cost of the investment (capital cost) †	2	3.21	64.2%
2.3.2	Cost - Cost of operation (including fueling and maintenance)	3	3.33	66.6%
2.3.3	Cost - Cost of decommissioning (including environmental remediation) †	3	3.26	65.2%
2.4.1	Cost for system integration – Maneuverability	4	2.78	55.6%
2.4.2	Cost for system integration – Load following	4	3.00	60.0%

2.4.3	Cost for system integration – Stability	1	4.00	80.0%
2.4.4	Cost for system integration – Easy to be integrated in local/regional grids	2	3.73	74.6%
2.4.5	Cost for system integration – Realistic solution for large scale storage	1	3.86	77.2%
2.5	External costs	2	3.63	72.6%
2.6	LCOE †	1	3.60	72.0%
2.7	Macro-economic impact	1	4.25	85.0%
2.8	Applicability for cogeneration	2	4.14	82.8%
2.9.1	Level of standards generated, rules and control - Maturity of the authorization process	3	3.52	70.4%
2.9.2	Level of standards generated, rules and control - Level of industrial codes and standards	2	3.51	70.2%
2.9.3	Level of standards generated, rules and control - Needs for technical support	4	2.55	51.0%
Social Life Cycle Assessment (So-LCA)				
3.1.1	Jobs created - Direct high-education jobs	1	4.82	96.4%
3.1.2	Jobs created - Jobs in contributing industries	1	4.42	88.4%
3.2	Impact on the local/regional business (partner with other business)	1	4.47	89.4%
3.3	Additional goods and services created	1	4.32	86.4%
3.4	Value of the knowledge generated and maintained for the future	1	4.73	94.6%
3.5	Impact on education	1	4.74	94.8%
3.6	Contribute to the reduction of inherited burdens (toxic wastes, military stocks)	1	3.72	74.4%
3.7	Impact on health improvement	2	3.82	76.4%
3.8	Impact on poverty	2	3.55	71.0%
3.9	Social level adoption of the technology	4	2.84	56.8%
3.10	Existing investment in RDI to develop the technology	2	3.71	74.2%
3.11	Dependency on government support (funding/ incentives, such as tax credits or subsidies) †	2	3.36	67.2%
3.12.1	Risks - Level of risk reflected in insurance	4	2.84	56.8%

	needs †			
3.12.2	Risks - Proliferation of sensitive materials †	1	3.18	63.6%
3.13.1	Equality of opportunities - Women's empowerment	1	3.34	66.8%
3.13.2	Equality of opportunities - For minorities, vulnerable social groups, Indigenous peoples, children, people with disabilities	3	2.97	59.4%

The results underscore nuclear power's versatility in addressing the environmental, economic, and social challenges that come with transitioning to a low-carbon future.

To summarize nuclear power's best performance among the assessed technologies, in descending value of obtained scores: The low carbon emissions (93.8% of ideal performance) make nuclear power one of the most viable options for reducing GHGs on a large scale, a key factor in fighting climate change. In terms of land occupation (92.2% perceived performance), nuclear power requires significantly less land than renewable energy sources like wind or solar, which often need vast areas to generate equivalent amounts of power. On the next three environmental indicators for which nuclear power showed the best sustainability performance, the absolute score (%) obtained is perhaps not as impressive; still, however, the other technologies made a less positive showing. Nuclear power demonstrated a comparatively low impact on biodiversity (77% of maximum performance), as its operations typically require smaller and more contained land areas, leading to less disruption of ecosystems. Nuclear power's lifecycle emissions of pollutants like NMVOC and PM2.5 are comparatively low (75% appraised performance), reinforcing its status as a clean energy source. Additionally, the impact of anticipated and design-based accidents remains comparatively low (68.6% appraised performance) due to the industry's stringent safety protocols. Technologies such as passive safety systems and safety-by-design principles further enhance the sector's ability to prevent and manage accidents, making nuclear power one of the safest large-scale energy options.

In the economic domain, nuclear power secured the best performance across six indicators, demonstrating its viability as a long-term solution for large-scale energy production. Its high-capacity factor (96.4%) means that nuclear plants can operate at near-full potential over long periods, providing a reliable and stable power supply—an essential requirement for meeting the growing global demand for electricity. The macro-economic impact of nuclear power is significant (85%), as it stimulates investment in infrastructure and creates long-term economic benefits. Nuclear power also exhibits global efficiency (80%), with advanced technology ensuring that more energy is extracted from each unit of fuel compared to other sources. This, coupled with a lower cost for system integration due to its stability (80%), reduces overall energy costs. Additionally, albeit with less ideal absolute scores, nuclear is seen as a realistic solution for large-scale energy storage (77.2%), essential for overcoming the intermittency challenges faced by renewables like wind and solar. The Levelized Cost of Energy (LCOE) for nuclear power, which considers the total lifecycle costs of energy production, is also competitive (appraised as 72% of ideal performance), particularly when the costs of managing carbon emissions are factored in.

Nuclear power's social impact is another area where it excels, with best performances across nine indicators. The technology generates numerous high-education jobs (appraised as 96.4% from maximum performance), not only within nuclear facilities but also in contributing industries (88.4%) such as manufacturing, research, and technology development. This job creation boosts local economies and has a ripple effect, promoting partnerships with regional businesses (89.4%) and generating additional goods and services in the process (86.4%). Nuclear power also plays a critical role in advancing knowledge

(94.6%) and education (94.8%). Its contribution to education in science, technology, engineering, physics, and mathematics fields is invaluable, helping to build a skilled workforce for the future. Nuclear energy preserves and generates knowledge for future generations, making it a central resource in the long-term development of energy technologies. As to less ideal but still comparatively strongest performances, nuclear energy contributes to societal well-being by helping to reduce inherited burdens such as toxic waste and military stockpiles (74.4%). Nuclear energy promotes equality of opportunity, particularly through women's empowerment (66.8%) in technical and managerial roles. This is a critical aspect of its contribution to the broader social agenda of gender equality. The non-proliferation of sensitive materials (63.6%) is another area where nuclear power shows leadership, seeking to control the contribution of technologies and materials to weapons development.

On the other hand, the assessment also reveals some significant challenges for nuclear power on each pillar of sustainability. Its relatively weaker performance on the following specific indicators and sub-indicators (in descending order) highlights critical limitations that must be addressed for nuclear to remain competitive and viable as a long-term energy solution.

Regarding environmental performance, nuclear power performs poorly in load following (60%)—the ability to adjust output in response to fluctuating demand. As more renewable energy comes online, energy grids need generators that can respond quickly to changing conditions. Nuclear plants, with their slower ramp-up and ramp-down times, struggle to fulfill this need, unlike gas plants or even emerging storage technologies that can quickly adapt to varying grid demands. Nuclear plants indeed are often considered less flexible than other forms of energy generation, particularly in their ability to respond to fluctuations in demand. Unlike natural gas plants, which can be ramped up or down quickly, nuclear reactors operate most efficiently when running continuously at full capacity. This lack of maneuverability (55.6%) makes nuclear less adaptable in modern energy grids that require flexibility to accommodate intermittent renewable energy sources like wind and solar.

Nuclear power was assessed as having the weakest performance in material recyclability (59.2% of ideal performance), which reflects a known challenge. The materials used in nuclear energy production, especially in reactor construction and fuel cycles, are often not easily recyclable. High-grade materials, including specialized metals and radioactive materials, require complex and costly processes to recycle, if they can be recycled at all. In contrast, other technologies like wind or solar involve more recyclable materials, such as metals and plastics, making their lifecycle more environmentally sustainable.

One of the most significant challenges facing nuclear energy is public perception and social acceptance (56.8% of ideal performance). Nuclear power continues to face widespread societal resistance, driven by concerns over safety, waste management, and the historical legacy of accidents. Despite its potential to provide low-carbon energy, many communities are reluctant to accept the construction of new nuclear facilities due to fears of radiation and long-term waste hazards. Public opposition, combined with political hurdles, slows down nuclear development and limits its broader adoption compared to renewable technologies, which are often viewed more favorably by the public.

The level of risk associated with nuclear energy, particularly in the event of a catastrophic accident, is reflected in the high costs of insurance (56.8% of ideal score). Nuclear facilities must carry substantial insurance policies to cover the potential damages in case of accidents or failures, which can be prohibitively expensive. The high-risk profile of nuclear energy, compounded by the complexity and longevity of managing radioactive waste, makes it far more expensive to insure compared to other energy technologies. This financial burden also impacts the overall economic viability of nuclear projects, particularly when competing against technologies that carry lower risk profiles, such as wind or solar.

Although nuclear energy is generally considered safe under normal operating conditions, the potential for catastrophic accidents, such as Chernobyl and Fukushima, has left an indelible mark on the perception of nuclear energy (56.2%). Even with advanced mitigation and prevention strategies, the consequences of a severe nuclear accident—both environmental and societal—are far more damaging than those associated with renewable energy technologies. These accidents can lead to long-term contamination of land, water, and ecosystems, requiring decades, if not centuries, for recovery.

One of the most significant drawbacks of nuclear energy is the generation of radioactive waste. The long-term impact of deposited nuclear waste is another area where nuclear energy was rated poorly (54.8%). While the volume of nuclear waste may be smaller compared to the wastes produced by fossil fuels, its high toxicity and long-term management present substantial environmental challenges (appraised as 53.2% of ideal performance). Safely storing and managing radioactive waste for hundreds or even thousands of years is a complex issue that other energy technologies, such as wind or solar, do not face. Deep geological repositories, currently the primary solution for storing high-level radioactive waste, pose risks over extended periods. Ensuring the safety and security of these waste deposits for future generations is a key challenge. Public concern about the potential environmental and health impacts of radioactive waste storage contributes to nuclear's low scores in this area.

Nuclear energy's impact on marine ecosystems (53.8% of maximum performance) is another area where it struggles. While nuclear plants do not emit direct pollution into the atmosphere, cooling systems often discharge large amounts of heated water into rivers, lakes, or oceans. This thermal pollution can disrupt aquatic life and ecosystems. Additionally, in the case of accidents, nuclear waste or other harmful substances can be released into water bodies, causing long-term damage.

Nuclear energy requires a significant amount of technical expertise and infrastructure (51% of ideal score) to be safely operated and maintained. This includes highly specialized labor, frequent technical inspections, and complex regulatory compliance. Other technologies, particularly renewables, are becoming increasingly decentralized and user-friendly, often requiring less intensive technical oversight and allowing for more straightforward integration into existing energy systems.

Overall, the assessment highlights that while nuclear power excels in many areas—particularly in reducing carbon emissions, ensuring grid stability, and contributing to economic development—it faces serious challenges in terms of environmental sustainability, economic flexibility, and social acceptance. The limitations identified in nuclear's material recyclability, waste management, and the social risks associated with severe accidents emphasize the need for ongoing technological innovation and policy development to address these critical issues. Improving corollary public trust and reducing the perceived risks of nuclear power are essential to gaining broader social acceptance.

Moreover, as noted above, the average (mean) rating obtained for nuclear sustainability performance on several (sub)indicators were accompanied by a noticeable degree of dispersion in opinion (larger standard deviations). These were discussed in Section 4 as they appeared, and are identified in Table 5.1 by daggers. These particular (sub)indicators would benefit from stakeholder discussion to elucidate the sources of disagreement, and the potential impact on nuclear's role in the energy transition.

Additionally, nuclear's inability to adapt quickly to fluctuating energy demands in modern, decentralized grids could limit its role as an energy source unless new technologies (such as small modular reactors) are able to offer improved maneuverability and load-following capabilities.

Addressing these weaknesses is crucial for nuclear power to maintain its position as a key player in the energy transition, particularly in the context of a future where flexibility, sustainability, and public confidence are critical to the success of energy technologies.

5.2 ECOSENS observations on the potential role of new nuclear technologies

In ECOSENS [5] an analysis of impact of societal and technological changes on the future energy market was performed to investigate the possible medium and long-term changes in the society and energy sector to create a basis for the identification of the possible roles of nuclear energy. The energy sector is complex and strongly influenced by economic growth and development, demographic evolutions, consumer behavior, technological advancements, policy changes, climate variability, geopolitical factors. In [6] a set of scenarios for nuclear power development in the European Union at the horizon of 2050 was developed, based on the preceding ECOSENS investigation [5] of energy demand, existing policies for decarbonization, and impact of societal and technological changes on the future energy market. The scenarios consider possible roles for new nuclear systems, such as SMRs and Generation IV. Such innovative systems hold significant promise in addressing many of the key drawbacks that have historically been associated with conventional nuclear power. These advancements focus on improving safety, environmental sustainability, flexibility, and social acceptance—areas where traditional nuclear technologies have faced criticism:

- Potential material recyclability - Generation IV reactors are designed with a much greater emphasis on fuel efficiency and the ability to recycle nuclear waste. Some of these reactors, such as fast breeder reactors, can use spent nuclear fuel from conventional reactors, significantly reducing the volume of long-lived radioactive waste. By reusing waste as fuel, these reactors not only reduce the burden on waste storage facilities but also extend the life of the nuclear fuel cycle. This increased recyclability addresses one of the major environmental concerns associated with traditional nuclear power.

- Radioactive waste and long-term impact of deposited wastes - SMRs and Generation IV reactors produce less high-level radioactive waste compared to traditional large-scale reactors. In particular, Generation IV reactors are designed to burn a higher percentage of nuclear fuel, leading to more efficient use of uranium and a reduction in the overall volume of waste. Additionally, some Generation IV designs, such as molten salt reactors (MSRs), have the potential to burn long-lived actinides, which are a major component of the radioactive waste that requires millennia of secure storage. This reduces the long-term environmental impact of deposited wastes and mitigates the issue of waste management for future generations.

- Impact of severe accidents - Both SMRs and Generation IV reactors prioritize passive safety features, which greatly reduce the likelihood of severe accidents. Many SMR designs incorporate features such as inherent cooling mechanisms that do not require external power or human intervention to maintain safety in the event of an emergency. This design philosophy significantly reduces the risk of catastrophic accidents, such as those experienced at Chernobyl or Fukushima. Generation IV reactors, including designs like the pebble-bed reactor, are also engineered to prevent core meltdowns, further improving safety outcomes. These improvements in safety directly address the concerns over severe accidents and their long-term environmental and social impacts.

- Marine ecotoxicity - New nuclear technologies, particularly SMRs, can mitigate the impact on marine environments by utilizing more efficient cooling systems that reduce thermal pollution. Some designs, such as those utilizing closed-loop cooling or advanced heat exchangers, minimize the release of heated water into natural water bodies, which has been a concern for marine ecosystems. In the case of Generation IV reactors, some designs are intended to operate at much higher temperatures, allowing for more efficient heat dissipation and reducing the environmental footprint of their cooling processes.

- Maneuverability and load following - One of the most significant advantages of SMRs is their ability to provide flexible power generation, addressing the historical limitations of traditional nuclear plants in terms of maneuverability and load-following capabilities. SMRs are designed to operate in a modular fashion, meaning that multiple smaller reactors can be deployed together, allowing for more responsive adjustments to electricity demand. Additionally, many SMR designs can ramp up and down more quickly than traditional reactors, making them well-suited to complement intermittent renewable energy sources like wind and solar. This flexibility allows nuclear power to play a more dynamic role in modern energy grids, which increasingly require generators that can quickly adapt to changing conditions.

- Reduced need for technical support - SMRs are often designed to be simpler to operate and maintain than conventional large-scale reactors. Because of their smaller size and modular nature, they can be pre-fabricated in controlled factory environments, reducing the complexity of onsite construction and decreasing the need for a large technical workforce. Many SMR designs are intended to operate autonomously for longer periods without needing as much manual intervention, which reduces both operational costs and the overall need for specialized technical support. This reduces one of the economic challenges of traditional nuclear plants, where technical expertise and infrastructure have been costly and resource-intensive.

- Social acceptance and risk perception - SMRs and Generation IV reactors are more likely to gain social acceptance due to their smaller size, enhanced safety features, and reduced environmental impact. SMRs, for instance, are seen as more versatile and less intrusive compared to traditional large nuclear plants, which are often met with public resistance. Their modularity allows them to be deployed in a wider range of geographic locations, including remote areas or smaller grids, where the need for large, centralized nuclear facilities is unnecessary. Additionally, the lower risk of accidents and the reduced scale of these plants can help alleviate public fears, making nuclear technology more palatable for communities and policymakers alike.

- Perceived risk and insurance needs - Generation IV and SMR technologies are also designed to mitigate the level of risk associated with nuclear power, which has traditionally driven high insurance costs. The inherent safety features, such as passive cooling and accident-tolerant fuel designs, drastically reduce the likelihood of severe incidents. In particular, SMRs are engineered with lower risk profiles due to their smaller reactor cores and enhanced safety mechanisms, which makes them less likely to cause catastrophic damage in the event of a failure. As a result, the insurance needs for these technologies are likely to be lower than for conventional reactors, thus reducing overall operational costs and improving their economic attractiveness. By minimizing the perceived risk, these advancements can also improve public confidence in nuclear power as a safe and reliable energy source.

- Non-proliferation and legacy waste management - Many Generation IV reactors are designed to use fuel more efficiently and can potentially burn existing nuclear waste, helping to reduce the stockpiles of toxic material generated by previous generations of nuclear reactors. For instance, fast neutron reactors can consume spent nuclear fuel that would otherwise require long-term storage, contributing to a reduction in the long-lived radioactive waste inventory. This contributes to alleviating inherited burdens such as waste from military stockpiles or older nuclear plants, a social benefit that could increase public support for new nuclear technologies.

However, despite their promising features, the new nuclear systems such as Generation IV reactors and Small Modular Reactors (SMRs), also come with several drawbacks. These include high initial costs, unproven long-term performance, and competition from renewable energy technologies. Furthermore, public acceptance and regulatory challenges can slow their adoption. As a result, while these new nuclear technologies hold promise, their widespread deployment will require overcoming these technical, economic, and societal barriers. Below some details on the drawbacks:

- Developmental stage: Most Generation IV reactors and SMRs are still in the early stages of development, with only a few prototypes or pilot projects in operation. The TRL for many designs is still low, meaning that significant engineering challenges remain before widespread commercial deployment can occur. These challenges include material durability, fuel cycle innovation, and reactor safety systems.

- Lengthy development and deployment: Despite being smaller and more flexible, SMRs and Generation IV reactors still face long lead times for development, testing, regulatory approval, and construction. In contrast, renewable technologies can be deployed more rapidly, which is critical in the context of urgent global decarbonization efforts.

- Unproven long-term performance: Given the novelty of these systems, there is limited data on their long-term operational performance, maintenance, and lifespan. Without extensive real-world experience, it's difficult to predict how they will perform under various conditions over decades of operation.

- High initial costs: Although SMRs and Generation IV reactors are expected to be more cost-effective in the long run, the upfront costs for research, development, and construction are substantial. The cost of designing and testing new reactors can run into billions of dollars, which can be prohibitive for many governments and companies.

- Uncertain economic viability: While SMRs are intended to be cheaper and faster to build than large nuclear plants, the economic competitiveness of these technologies remains uncertain. If economies of scale are not achieved—such as through mass production—their cost advantage could be undermined. Moreover, competition from rapidly advancing renewable energy technologies could make nuclear less economically attractive.

- Falling costs of renewables: The rapid decline in the cost of renewable energy technologies like solar and wind, coupled with improvements in energy storage solutions, poses a challenge to the economic competitiveness of new nuclear technologies. The lower capital cost and quicker deployment of renewables make them an attractive alternative to nuclear, especially in countries aiming for a swift transition to low-carbon energy.

- Regulatory challenges: Nuclear regulation is stringent, and any new reactor design must undergo rigorous safety reviews. Given the lack of familiarity with the unique aspects of Generation IV and SMR designs, regulatory bodies may require significant time to assess these technologies, delaying deployment. This can be particularly problematic for SMRs, where streamlined and harmonized regulation is essential to their economic viability.

- Fuel cycle risks: Certain Generation IV reactors, such as those that use fast-neutron reactors, rely on advanced fuel cycles, including reprocessing spent nuclear fuel. While this can reduce waste, it can also produce Plutonium, raising concerns about nuclear proliferation if the materials fall into the wrong hands. Ensuring that these systems are adequately safeguarded is a significant challenge.

- Supply chain maturity: The nuclear industry has a relatively small global supply chain, and the specialized components required for new reactor designs may not be readily available. Developing a robust supply chain for advanced reactors could take time and investment.
- Public skepticism: Nuclear energy remains a highly contentious issue for many communities. The historical accidents at Chernobyl, Fukushima, and Three Mile Island continue to shape public perception, making it difficult for new nuclear technologies to gain widespread social acceptance. Even though Generation IV reactors and SMRs are designed to be safer, public fears about nuclear energy, waste disposal, and potential accidents persist.

Despite these challenges the new nuclear technologies like Generation IV reactors and SMRs offer the potential to significantly reduce many of the longstanding drawbacks of traditional nuclear power. Through enhanced safety features, improved recyclability of materials, reduced radioactive waste, and greater operational flexibility, these advancements address critical concerns in the environmental, economic, and social domains. SMRs' ability to provide more flexible, more reliable energy while fitting into modern grids alongside renewables makes them particularly valuable in the transition to a low-carbon future. Likewise, Generation IV reactors' innovations in fuel efficiency, waste management, and non-proliferation offer solutions to some of the most pressing challenges in nuclear energy.

6. Conclusions

(C1) Assessing energy technologies in the EU's energy transition is crucial for informed decision-making, as it enables policymakers to balance sustainability, reliability, and cost-effectiveness. By including iRES, hydro, nuclear, and gas, the ECOSENS lifecycle sustainability assessment ensures that diverse technological options are considered, in view of fostering a more resilient energy mix, based on the technologies considered as key players in the energy transition period. Periodic assessment of energy technologies will be essential for informed decision-making, allowing to adapt strategies based on the evolving capabilities of the energy technologies. As technologies advance and energy markets shift, regular assessments can ensure that the most efficient, sustainable, and cost-effective solutions are prioritized. Continuous involvement of diverse stakeholders will keep the process transparent and responsive to societal needs. Such a dynamic adaptative approach should be adopted to help align energy policies with the latest innovations and market trends, promoting a more resilient and flexible energy transition.

(C2) Policymakers, energy producers, environmental groups, industry representatives, and technical experts should all contribute to assessment, as they provide insights into feasibility, market trends, and environmental impacts. Equally important is the inclusion of the public, whose support is crucial for implementing long-term energy strategies. This collaborative approach should not only strengthen decision-making but also foster a sense of ownership and trust in the energy transition process.

(C3) To achieve reliable results in the assessment, participants must possess adequate information and knowledge to critically appraise various indicators and make sound judgments. This process is enhanced by providing easy access to relevant, high-quality data and insights from existing literature, presented in a standardized, clear and digestible form. The ECOSENS methodology innovates by providing a set of fiches that detail key indicators, summarize relevant and up-to-date data, and indicate corresponding references. By accessing these resources, participants can quickly enhance their understanding, enabling them to respond in a more informed and knowledgeable manner. However, it may be difficult to verify how much reference each participant effectively makes to these knowledge resources.

(C4) The comprehensive ECOSENS set of 62 indicators and sub-indicators, validated by stakeholders, covers all critical dimensions of energy technologies, including the sustainability pillars of environmental performance, economic viability, and social impacts. This holistic approach ensures that each technology is considered from multiple perspectives, capturing both its strengths and weaknesses. By systematically applying these indicators, the advantages and drawbacks of various energy technologies can be quantified and compared, leading to a more objective and balanced assessment. Ultimately, this comparative assessment is distilled into final figures of merit, which provide a clear, data-driven basis for decision-making in the selection of optimal energy solutions for the energy transition.

(C5) The methodology is enhanced by the application of weighting, allowing the relative importance of each indicator and sub-indicator to vary according to different societal perspectives and priorities. This flexibility recognizes that environmental, economic, and social factors are valued differently depending on the context or stakeholder group. For instance, decision-makers focused on long-term sustainability may prioritize environmental indicators, while those primarily concerned with economic growth might assign greater weight to cost-effectiveness. Typically, the weighting process is carried out by policymakers or experts responsible for shaping the strategic vision of the energy system. However, it can also be adjusted to reflect broader societal values, ensuring that the assessment aligns with the diverse interests and priorities within the community.

(C6) In the current ECOSENS investigation of lifecycle sustainability performance, two weighting approaches were applied to provide a comprehensive assessment of four key energy technologies. The first approach employs equal weighting, where all indicators and sub-indicators are considered to have the same level of importance. This method offers a straightforward and unbiased comparison by treating each aspect uniformly. The second approach involves a more nuanced assessment, where weights are assigned based on insights from a diversified group of stakeholders (S1), and a panel of 26 technical experts (S2). These stakeholders and specialized experts, who possess relevant knowledge of energy systems and sustainability issues, contributed their expertise to determine the relative importance of each indicator and sub-indicator.

(C7) The assessment process, along with the results obtained, illustrates that the developed methodology—despite its complexity and reliance on extensive knowledge—is both practical and effective. This approach, though intricate, successfully captures the multifaceted nature of energy technologies and their impacts. Stakeholders can actively engage in the process, provided they are willing to invest time and effort into reading, learning, discussing, and expanding their understanding of the subject matter. Their participation hinges on a commitment to continuously enhance their knowledge, which is crucial for contributing meaningfully to the assessment and ensuring that the results reflect a well-rounded and informed perspective. This active involvement not only enriches the assessment but also fosters a more collaborative and transparent decision-making environment.

(C8) The final results of the assessment reveal that, according to the respondents, despite some differences in opinion (displayed by error bars) the sustainability performance differences among the considered technologies are relatively minor. While there are some inter-rater variations in how the technologies are perceived, the performance scores for the four technologies generally fall within a narrow range, typically between 3 and 4 on the scale. None of them received a score approaching the ideal maximum of 5. This clustering of mean scores suggests that all the technologies are seen as having similar levels of effectiveness or suitability, with no single option emerging as significantly superior or inferior to the others. Moreover, the two groups assessing and later, weighting the indicators did not reveal substantial differences in judgment. Such a unified profile underscores the need for a nuanced analysis to discern subtle differences and for ongoing efforts to differentiate the performance and perception of each technology. In particular, attention must be paid to the particular (sub)indicators and technologies whose mean rating revealed noticeable dispersion in opinion. Nuclear power showed several such areas, whereas hydro stood out as the technology that was least consensually understood. On the other hand, all these technologies are considered valuable for the energy transition process. Differences between them are generated by the evolutions of the market and of the technologies itself, and are context-dependent.

(C9) Gas technology often receives lower scores due to its environmental impact, as it still emits greenhouse gases despite being cleaner than coal. Its reliance on finite fossil fuel reserves raises concerns about long-term sustainability. The rapid advancement of renewable technologies can make gas appear less innovative. Additionally, the high costs and complexity of gas infrastructure, coupled with challenges in transitioning away from it, can further contribute to its lower assessment scores.

(C10) The nuclear power option received the highest overall score due to several factors. Nuclear technology offers a high energy density and can produce large amounts of electricity with minimal greenhouse gas emissions, making it a strong candidate for reducing carbon footprints. Additionally, it provides a stable and reliable energy source, with consistent output unaffected by weather conditions. The composition of the assessment group, with more than 50% members having knowledge in the nuclear field, likely influenced the results. This dominant representation may have contributed to a more favorable evaluation of nuclear technology, reflecting a deeper understanding and appreciation of its benefits and potential (as well as any affective bias on the part of professionals who are deeply invested in improving nuclear energy systems and safety).

(C11) The second position in the assessment was achieved by either Hydro or iRES, depending on the specific sustainability pillar under consideration. Hydro technology is valued for its renewable nature and reliable energy generation, particularly in regions with ample water resources. In contrast, iRES (intermittent renewable energy sources) like wind and solar are recognized for their potential to reduce greenhouse gas emissions and their alignment with long-term sustainability goals. The variation in the second-place ranking reflects the different strengths and suitability of these technologies in various contexts, highlighting that both have significant contributions to the energy transition, but excel in different aspects of the assessment criteria. Intermittent renewable energy sources face, at least currently, several drawbacks. Their energy production is variable, dependent on weather conditions, which can impact reliability. Waste management for components like solar panels and wind turbine blades is still developing, posing environmental challenges. The use of rare materials for these technologies raises concerns about resource scarcity and environmental impact. Additionally, iRES require large areas for deployment, which can lead to land use conflicts. Finally, their Energy Return on Investment (EROI) can be relatively low, affecting their overall efficiency and economic viability. Hydro technology has several drawbacks. Large-scale hydroelectric projects can cause significant environmental impacts, such as habitat destruction and changes in river ecosystems. They may also lead to displacement of local communities due to reservoir creation. Additionally, hydro power is dependent on water availability, which can be affected by seasonal variations and climate change. The construction and maintenance of dams can be expensive and involve complex engineering challenges. Beyond these drawbacks, both iRES and Hydro have important potential for improvement, and capacity for deployment. The current climate change crisis, combined with the difficulties of nuclear to find largely accepted solutions for the radioactive wastes, offers an enormous window for the development of iRES. The critical issue is the insufficient development of the large-scale storage, but this drawback may be diminished by the progress of the science and technology. Vigilance is needed, as discussed above, regarding the fact that hydro simultaneously appears to be the least well-known technology, its mean ratings standing out in terms of dispersion (larger standard deviations).

(C12) The weighting process can offer a means to align the assessment process and analytic outcomes with the broader context of societal demands and policy-making. In the ECOSENS study, the weights were derived from consultations with stakeholders (of whom only 6 pronounced themselves) and 26 technical experts. It is important to recognize that the perspectives of these stakeholders and experts, particularly their views on future trends and developments, may differ significantly from those of policy-makers. While, in the present analysis, applying these weights did not result in dramatic changes in the outcomes, this may not always be the case. In policy contexts where specific priorities or objectives are being targeted, the application of different weighting schemes could lead to considerable variations in the final scores and ranking of options. Thus, tailoring the weighting process to reflect the specific goals of a given policy (for example: representativeness of societal demand; responsiveness to expert advice; alignment with energy regulations; etc.) may result in distinct hierarchies and outcomes that better support informed decision-making.

(C13) The current assessment provides a foundational basis for testing the methodology by engaging both technical experts and key stakeholders. However, a critical challenge lies in ensuring the genuine, meaningful participation of a sufficiently large set of individuals in the assessment process, particularly when evaluating complex indicators. The depth of engagement is crucial, as it directly influences the quality and credibility of the outcomes. Participants must be highly invested in the process, dedicating sufficient time and effort to make informed decisions rather than merely completing the questionnaire task without relevant reflection. Alongside the burden of judging 62 (sub)indicators x 4 technologies, the consideration of the entire lifecycle heightens the complexity of each judgment. A potential issue that arises could be a tendency for respondents to approach the assessment in a formalistic manner, which may lead to superficial or even random answers. This risk is heightened when participants are expected to consult detailed resources, such as developed indicator fiches, technical documents, or background data, as part of the decision-making process. When faced with additional information, participants may feel overwhelmed or disengaged, leading them to provide less thoughtful responses. This can result in data that does not accurately reflect the intended measures or objectives of the assessment.

(C14) Marginal values in survey responses often emerge due to factors such as respondent fatigue, lack of engagement, or misinterpretation, which can result in superficial or inconsistent answers. These marginal values can undermine the quality of data, making it difficult to draw reliable conclusions. To mitigate this, various measures have already been implemented, such as the clear and concise formulation of questions, the use of appropriate scaling, inclusion of a "don't know" option, and the development of simplified fiches to document and explain the indicators. These strategies applied by ECOSENS aim to reduce confusion and encourage more thoughtful, accurate responses from participants. Additionally, controls could be introduced at the data analysis stage, by e.g. removing or re-weighting outlier responses to diminish the distorting effects of marginal values. However, in the current assessment exercise, this approach was not applied due to the relatively small sample size (40 participants) and the formal difficulty of distinguishing between errors and genuinely marginal but meaningful data points. With such a small participant pool, the elimination of marginal values risks omitting potentially valid insights. As the ECOSENS project moves forward, particularly in the context of WP2, efforts will be dedicated to addressing these dimensions of quality in a systematic way. Future activities will identify useful refinements in assessment survey construction, recruitment and engagement of participants, task conditions, and finally data characterization and analysis. Advanced statistical techniques such as factor analysis may be applied to draw new insights from the existing data. Stakeholder workshops (webinars) could be organized to discuss the most contentious (most widely dispersed) assessments identified by this report. These activities will be reported in ECOSENS D2.5, “Recommendations for future development of the methodology to assess sustainability,” and potentially in a peer-reviewed journal submission.

7. References

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