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EVALUATING ECONOMIC, ENVIRONMENTAL, AND SOCIAL IMPACTS OF ADOPTING FUSION ENERGY IN SAUDI ARABIA

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Abstract

Fusion energy is increasingly recognized as a potential game-changer in addressing the grand challenge of achieving deep decarbonization while ensuring long-term energy security. Recognizing the uncertainty surrounding fusion energy's technological maturity, commercialization timelines, and cost trajectories, this study adopts an anticipatory foresight approach tailored to high-uncertainty contexts. The research employs a mixed-methods framework incorporating horizon scanning, expert elicitation, trend analysis, and exploratory scenario planning. These methods were selected to account for deep technological uncertainty (e.g., plasma containment breakthroughs, cost convergence, fuel supply chain development), as well as systemic uncertainties related to socio-political acceptance and infrastructure readiness.

For the case of Saudi Arabia, three distinct scenarios -optimistic, moderate, and conservative- are developed to reflect a spectrum of plausible futures. Under the optimistic scenario, fusion could supply 10–15% of Saudi Arabia's electricity mix by 2045 (50–75 TWh annually). The moderate scenario forecasts a 5–10% contribution by 2050 (25–50 TWh), while the conservative case sees fusion reaching under 5% by 2060 (<25 TWh). These projections are framed within the broader uncertainty landscape, with sensitivity analyses on cost assumptions, technological learning curves, and policy interventions.

A comparative assessment of anticipatory methodologies under these uncertainty levels underscores the limitations of deterministic forecasting and the value of scenario-based planning in guiding long-term energy policy. While fusion's economic feasibility remains uncertain, potential cost parity with advanced nuclear fission and gas-fired plants by mid-century is plausible. The paper concludes with strategic policy recommendations to reduce uncertainty and accelerate fusion adoption: increasing national R&D funding, fostering international and public-private collaborations, investing in adaptive grid infrastructure, and developing flexible regulatory frameworks.

1. INTRODUCTION

Fusion energy is a form of power generation that seeks to replicate the energy-producing processes of the sun and other stars. It is achieved by fusing lighter atomic nuclei, such as isotopes of hydrogen (deuterium and tritium), to form a heavier nucleus, such as helium. This process releases enormous amounts of energy, primarily in the form of heat, due to the conversion of a small amount of mass into energy [1].

Fusion energy is an emerging technology as evidenced by its developmental stage, transformative potential, and alignment with global energy and sustainability goals. While the concept of harnessing nuclear fusion -the process that powers the sun- to generate electricity has been explored for decades, recent advancements have brought it closer to practical application.

Fusion energy is defined by several key characteristics. It is grounded in technological innovation, relying on advanced principles of plasma physics and magnetic confinement, such as tokamaks and stellarators. Recent progress in materials science, particularly the development of high-temperature superconducting magnets, has significantly enhanced the stability of plasma confinement [2]. Despite these advancements, fusion remains in the experimental and prototype phase, with large-scale projects like the International Thermonuclear Experimental Reactor (ITER) striving to achieve net energy gain [3]. Commercial viability, however, remains years away, though private-sector initiatives such as Commonwealth Fusion Systems and Helion are accelerating progress toward more compact and efficient reactor designs [4].

The objective of the current study is to evaluate the potential impacts and adoption scenarios of fusion energy in Saudi Arabia. The research presents several scenarios that detail the phased integration of fusion energy into Saudi Arabia's national grid, each with strategic policy recommendations aimed at maximizing benefits while mitigating risks.

2. METHODOLOGY

This study employs a multi-phase, mixed-methods technology foresight framework to evaluate the adoption of fusion energy in Saudi Arabia under conditions of uncertainty. This approach is designed to be systematic in four phases. The process integrates several foresight tools in a logical sequence, where the output of one phase serves as the input for the next.

2.1. Phase 1: Scoping and Intelligence Gathering

This initial phase establishes the analytical foundation:

— **Literature Review & Theoretical Framework:** The process begins with a comprehensive review of existing literature on fusion energy to construct a theoretical framework. This identifies the primary variables influencing fusion adoption, such as technological milestones, economic viability, and key stakeholders.

— **Horizon Scanning:** This tool is used to scan for "weak signals" and recent developments not yet fully captured in academic literature. It involves reviewing news, industry reports, and conference proceedings to identify recent breakthroughs (e.g., NIF's ignition, private sector progress), emerging players, and shifts in global policy. The output is a broad map of the current state of fusion technology and its ecosystem.

2.2. Phase 2: Analysis of Drivers and Uncertainties

This phase takes the variables identified in Phase 1 and analyzes them in depth.

— **Trend Analysis:** This step provides a quantitative, data-driven layer to the analysis. By examining trends in publications, patents, and public funding over time, we can measure the momentum of R&D and commercial interest. This provides an objective basis to assess whether interest in fusion is growing, stagnating, or declining.

— **PESTLE Analysis:** This is the core of the uncertainty analysis. It takes the key variables and systematically examines them through six lenses (Political, Economic, Social, Technological, Legal, Environmental). This is how uncertainty is handled. Rather than focusing only on technology, it forces a holistic assessment of non-technological factors that could enable or block fusion's deployment, such as geopolitical alignment, cost-competitiveness with solar, public perception, and regulatory hurdles.

2.3. Phase 3: Synthesis and Scenario Construction

This phase synthesizes the findings to create plausible future narratives:

— **Identifying Critical Uncertainties:** From the PESTLE and Trend analyses, we identify the two most impactful and uncertain drivers that will shape the future of fusion energy. For this study, these are:

- The pace of technological maturation and commercialization (e.g., overcoming engineering hurdles, achieving cost reductions).
- The level of sustained policy and financial support (e.g., government funding, private investment, favorable regulations).

— **Building Scenario Logic:** The three scenarios (Optimistic, Moderate, Conservative) are constructed by combining different outcomes for these two critical uncertainties.

- **Optimistic Scenario:** Assumes *rapid* technological progress converges with *strong and unwavering* policy and financial commitment. The Optimistic Scenario depends on the rapid and successful resolution of all major subsystem challenges (e.g., rapid advancement to TRL 7-9 across the board).
- **Moderate Scenario:** Assumes *steady but incremental* technological progress combined with *consistent but not accelerated* support. The Moderate Scenario assumes significant but slower-than-expected progress, potentially facing delays in critical subsystems such as tritium breeding.
- **Conservative Scenario:** Assumes *significant technological delays or roadblocks* and/or *faltering or inconsistent* policy and financial support. The Conservative Scenario reflects the possibility that fundamental challenges, for instance, first wall material survivability, prove exceptionally difficult to resolve.

— **Quantifying the Scenarios:** Each narrative is then quantified by projecting its impact on Saudi Arabia's energy mix by a specific year, based on a set of explicit assumptions (e.g., total electricity demand reaching 500 TWh by 2050).

2.4. Phase 4: Impact Evaluation and Strategy Formulation

The final phase uses the scenarios as a tool for strategic planning:
- **Impact Assessment:** The PESTLE framework is revisited to evaluate the potential economic, social, and environmental impacts of each scenario on Saudi Arabia.
- **Stakeholder and Policy Analysis:** Key local and international stakeholders are mapped to identify potential partners and enablers. Based on this, actionable Policy Recommendations are developed to help Saudi decision-makers navigate the uncertainties, mitigate risks, and create the conditions necessary to achieve the benefits of fusion energy when it becomes viable.

This methodological sequence offers a transparent and replicable approach. By making explicit how each method feeds into the next, the study demonstrates how uncertainty is addressed through layering multiple foresight tools rather than relying solely on extrapolated trends.

3. APPLICATION OF TECHNOLOGY FORESIGHT TOOLS

To conduct a robust study on the adoption and impacts of fusion energy in Saudi Arabia, various technology foresight tools and methods can be employed. These approaches help anticipate future developments, identify uncertainties, and explore plausible scenarios. By integrating these tools and methods, the study will provide a comprehensive and strategic assessment of fusion energy's role in Saudi Arabia's energy future. Below are some key tools and methods applied in the current study.

3.1. Horizon Scanning

Horizon Scanning is a systematic approach used within the framework of Technology Foresight to identify, analyze, and interpret emerging trends, technologies, and potential risks or opportunities. It involves collecting and analyzing information about developments that could have significant impacts in the future, allowing organizations to anticipate changes and adapt accordingly.

Horizon Scanning was performed partially earlier in this research, as in the literature that reviewed and showed some important advancements in fusion energy. Horizon Scanning involves systematically identifying and analyzing emerging trends, such as the growth in research activity evident from the increasing number of records, to anticipate technological advancements and their implications as shown in Fig. 1 which shows the evolution of records related to Fusion Reactors or Fusion Energy from 2010 to mid-2025. The number of records is generally growing over the years, with a peak in 2022 at 3137 records, followed by close records in 2023 and 2024. By mid-2025, the records reached 2290. So, it is expected to reach more than 4000 records by the end of the year. Overall, this suggests a period of increased interest and research activity in the field of fusion energy. The data indicates a dynamic and evolving landscape for fusion energy research and development over the analyzed period.

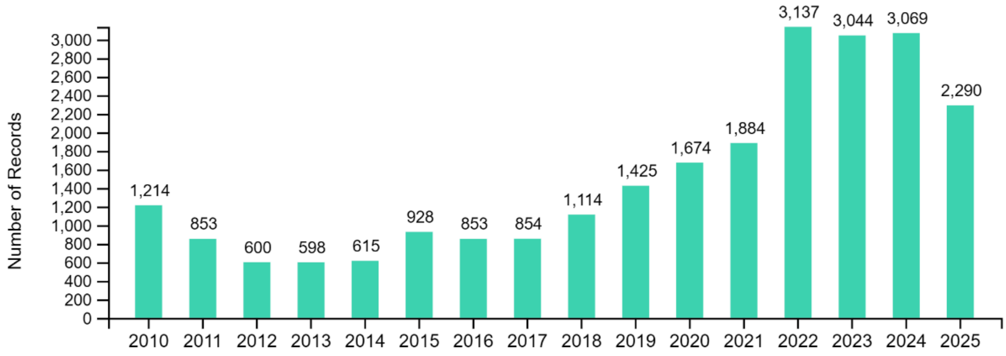

FIG. 1. Fusion energy records evolution over time (2010 – mid-2025) [5].

3.2. Trend Analysis

Fig. 2 represents a trend analysis within the technology foresight framework, as it examines historical data on grant funding amounts (bars, left axis) and the number of grants awarded (line, right axis) for fusion energy between 2010 and 2025. Trend analysis is used not merely to predict the future but to provide a baseline evidence base by detecting growth patterns, inflection points, or declines in innovation activity. Fig. 2 combines grant funding data (bars, left axis) with the number of grants awarded (black line, right axis) for fusion energy research between 2010 and mid-2025, as illustrated below:

— Colored bars (stacked by region: Europe, U.S., U.K.) show the total dollar amount of grants awarded each year (scale on the left, in millions of USD). For example, in 2014 there was a very large spike, with funding exceeding $800M, largely driven by Europe. Other visible peaks occur around 2017 and 2019, though at much smaller scales (~$100M).

— Black line represents the number of grants awarded annually (scale on the right). The line shows fluctuations between 20 and 45 grants per year, peaking around 2015–2016 and 2018.

Fig. 2 shows that the reported global funding for fusion energy is uneven, with a few exceptional spikes (particularly 2014 in Europe) dominating the totals. It shows also that the number of grants, however, is more stable year-to-year, suggesting that while many projects continue to receive support, the size of funding varies greatly depending on large strategic programs or one-off mega-grants. The discrepancy between the smoothness of the black line and the volatility of the bars highlights how commercial readiness and research momentum cannot be inferred from funding amounts alone, i.e., both *scale* and *frequency* of grants must be considered.

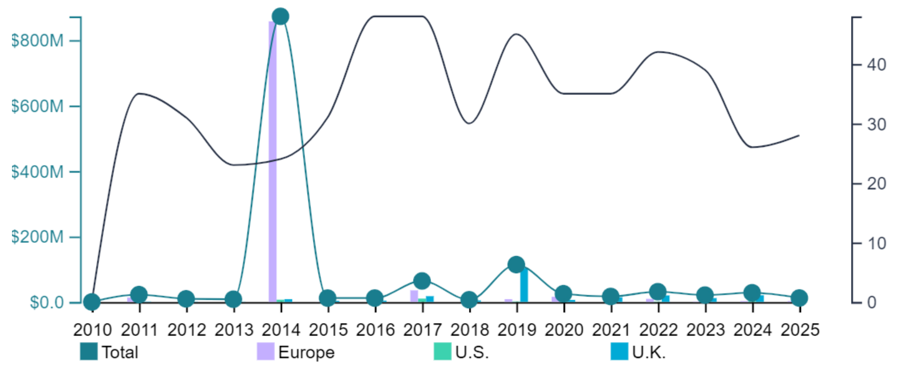

FIG. 2. Fusion Energy Public Funding and Grants (2010 – mid-2025) [5].

The data in Fig. 3 shows that the prevalence of topics related to Fusion Energy has varied over the years. Fusion Experiments saw a gradual increase from 2016 to 2023, indicating a growing focus on experimental research. Magnetic Fusion also showed peaks in 2012, 2016, and 2023, suggesting intermittent interest in this area. Energy Produced had a notable increase in 2016 and 2022, indicating a heightened focus on energy generation. Tokamak Design, Materials Science, Plasma Discharge, Superconductors, and Clean Fuels also showed varying levels of prevalence over the years, with some years seeing more attention than others. Overall, the data reflects the evolving and dynamic nature of research and development in the field of fusion energy.

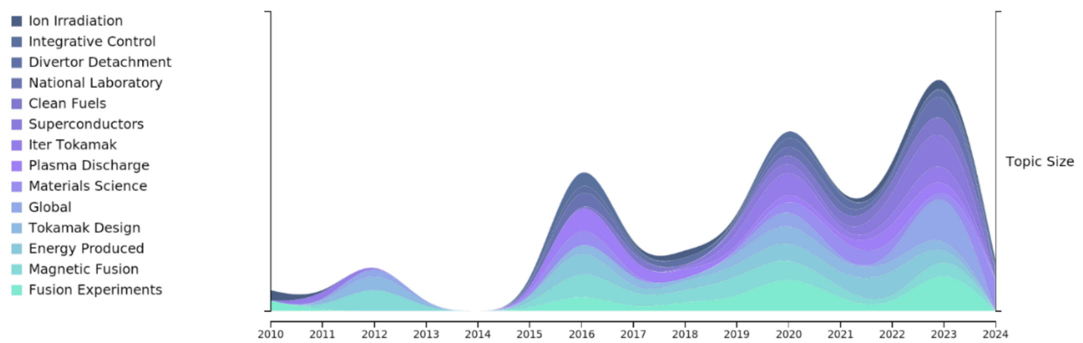

FIG. 3. Fusion energy trends evolution over time (2010-2024) [5].

3.3. PESTLE Analysis

PESTLE Analysis is a strategic framework used to examine external macro-environmental factors that influence an organization, project, or industry. The acronym represents Political, Economic, Social, Technological, Legal, and Environmental dimensions, providing a structured approach to identify opportunities and challenges in the external environment. This tool is widely used for strategic planning, risk assessment, and understanding the broader context in which decisions are made. For instance, it considers government policies, market trends, societal attitudes, technological advancements, regulatory compliance, and environmental concerns to help stakeholders align their strategies with external realities.

3.3.1. Political Impacts

The successful commercialization of fusion energy would have profound political implications for Saudi Arabia, reshaping its domestic and international political landscape. Here are the key political impacts:

a) **Strengthened Global Influence:** By investing in and potentially exporting fusion energy technology, Saudi Arabia could position itself as a global leader in clean energy innovation, enhancing its political clout in international forums [7]. Fusion energy development could foster partnerships with countries and organizations leading in fusion research, such as the European Union, the U.S., and China, deepening geopolitical ties.

b) **Shifts in Regional Power Dynamics:** Adopting fusion energy could potentially decrease tensions linked to fossil fuel resources, as cleaner energy sources reduce the strategic importance of oil and gas [6]. Fusion energy development could promote regional collaborations in science and technology, fostering goodwill among Gulf Cooperation Council (GCC) nations and beyond [7].

3.3.2. Economic Impacts

Fusion power can produce nearly 4 million times more energy per kilogram of fuel than fossil fuels like coal, oil, or gas. Investing in future fusion technology is expected to create jobs, stimulate economic growth, and enhance the nation's energy security, contributing to a cleaner energy system for future generations. This investment aims to bring, for instance, the UK closer to connecting fusion energy to the national grid by the 2040s [8]. The effective commercialization of fusion energy holds the potential to significantly impact Saudi Arabia's economy in several ways:

a) **Energy Diversification and Security**: Integrating fusion energy into Saudi Arabia's energy mix would enhance energy security by reducing reliance on oil and natural gas. This diversification aligns with the Kingdom's Vision 2030, which aims to generate 50% of its energy from renewable sources by 2030 [9].

b) **Economic Diversification**: Investing in fusion energy technology could stimulate the development of new industries and job creation, contributing to economic diversification. This move would reduce the economy's dependence on oil revenues and foster growth in high-tech sectors.

c) **Long-Term Economic Stability**: Reducing dependence on oil exports through fusion energy adoption would shield the economy from oil price volatility, leading to more stable and predictable economic growth.

3.3.3. Technological Impacts

The successful commercialization of fusion energy would have profound technological impacts on Saudi Arabia, driving innovation and transformation in various domains. Some of the key impacts follow:

a) **Advancement in Energy Infrastructure:** The deployment of fusion energy would require significant upgrades to the national grid to accommodate stable, large-scale, and consistent power generation. The extreme conditions of fusion reactors (e.g., high heat and radiation) would also foster innovation in heat-resistant materials and technologies.

b) **Boost to Research, Development and Innovation (RDI):** For instance, investment in fusion energy would promote cutting-edge research in plasma physics, materials science, and energy technologies. Saudi Arabia could become a hub for international collaborations with institutions and countries leading in fusion research, such as ITER.

c) **Innovation in Energy Storage and Transmission:** By the development of energy storage technologies, efficient energy storage solutions would be developed to complement fusion energy and manage surplus electricity [10]. Also, transmission networks would be enhanced so that high-capacity and efficient transmission technologies would be necessary to distribute fusion energy reliably across the Kingdom.

3.3.4. Sociological Impacts

Socio-economic analyses reveal the transformative potential of fusion energy. The societal benefits of fusion adoption, including job creation, economic diversification, and energy security were discussed [11], [12]. The commercialization of fusion energy could have significant sociological impacts on Saudi Arabia, influencing various aspects of society. Key potential impacts include:

a) **Transformation of the Workforce:** Fusion energy technology requires highly skilled labor for research, development, and maintenance, driving demand for technical education and specialized training. A transition from fossil fuel-based jobs to renewable and fusion energy sectors could lead to reskilling initiatives and reallocation of the workforce [13].

b) **Public Perception and Acceptance:** The adoption of clean energy solutions like fusion energy might foster a culture of environmental awareness and sustainability within Saudi society. Public education campaigns would be necessary to address misconceptions and fears regarding nuclear technologies, even though fusion is inherently safer than fission. Cleaner energy and environmental conservation would enhance overall community well-being and quality of life.

3.3.5. Legal Impacts

The effect of fusion energy would have significant legal implications for Saudi Arabia as the Kingdom adapts its regulatory framework to support the deployment and governance of this advanced energy technology. Some of the legal impacts follow:

a) **Development of Fusion-Specific Regulations:** Saudi Arabia would need to create regulations specifically tailored to fusion energy, distinct from fission nuclear energy laws, due to differences in safety, waste, and operational risks. Clear procedures for licensing and permitting fusion energy facilities would be required, ensuring compliance with international safety standards [14].

b) **Compliance with International Treaties:** Saudi Arabia would need to adhere to international agreements and guidelines, such as those from the International Atomic Energy Agency (IAEA), to ensure safe and responsible use of nuclear technologies. Legal mechanisms would be necessary to regulate the export of fusion-related technologies, aligning with non-proliferation treaties and agreements.

3.3.6. Environmental Impacts

The prosperity of fusion energy in Saudi Arabia could lead to substantial environmental benefits, including reduced greenhouse gas emissions, improved air quality, and better management of natural resources, thereby supporting the Kingdom's sustainability objectives. Positive environmental impacts of adopting fusion energy in Saudi Arabia include:

a) **Reduction in Greenhouse Gas Emissions and Air Pollution**: Fusion energy generates electricity without emitting greenhouse gases during operation, which would help Saudi Arabia reduce its carbon footprint and align with its goal of achieving net-zero carbon emissions by 2060. Transitioning to fusion energy would reduce reliance on fossil fuels, leading to lower emissions of pollutants such as sulfur dioxide (SO_2) and nitrogen oxides (NO_x). This shift would improve air quality and public health [15].

b) **Mitigation of Desertification**: By providing a sustainable and clean energy source, fusion energy could support technologies like desalination, which are essential for combating desertification and water scarcity in Saudi Arabia.

c) **Minimal Radioactive Waste**: Fusion energy produces significantly less long-lived radioactive waste compared to traditional nuclear fission reactors, reducing the environmental challenges associated with waste management [16].

d) **Conservation of Natural Resources**: Adopting fusion energy would decrease the extraction and consumption of fossil fuels, preserving natural resources and reducing environmental degradation associated with mining and drilling activities.

3.4. Scenario Planning

The objective here is to develop multiple future scenarios to explore different pathways of fusion energy adoption and its impacts under various conditions (e.g., rapid adoption, gradual integration, limited use). This will help addressing uncertainty in fusion development timelines. Table 1 shows three scenarios (Optimistic, Moderate and

Conservative) outlining potential paths for Saudi Arabia's adoption of fusion energy. The following assumptions were made:

1. Total electricity consumption grows to 500 TWh by 2050.
2. Renewable and fusion contributions replace hydrocarbon-based electricity in varying degrees depending on the scenario.

Taking into consideration that Fusion Energy's large-scale deployment (especially >10% of the grid) requires not only technological breakthroughs but also significant political and financial commitment, the numbers provided in Table 1 are estimates and depend on multiple assumptions about Saudi Arabia's energy growth, technological advancements, and policy commitments. Below is a breakdown of the realism of these scenarios. Fig. 4 demonstrates a visualization of the energy mix contributions under the three scenarios, showing the relative shares of fusion, renewables, and hydrocarbons in Saudi Arabia's electricity generation.

The scenarios presented in Table 1 outline potential pathways for Saudi Arabia's fusion energy adoption, but their realism varies significantly. The Optimistic Scenario (10–15% by 2045) is highly ambitious, requiring fusion commercialization, large-scale deployment, and grid integration within compressed timeframe—challenges that make it ambitious but plausible under accelerated conditions given current technological and economic constraints. The Moderate Scenario (5–10% by 2050) is plausible if Saudi Arabia invests heavily in fusion R&D, infrastructure, and regulatory frameworks over the next two decades, positioning itself as an early adopter. The Conservative Scenario (<5% by 2060) is the most realistic, as it aligns with the cautious adoption of emerging energy technologies, especially given the uncertainties surrounding fusion's commercial viability. Overall, while early investment could accelerate fusion adoption, a gradual and complementary integration with renewables and hydrocarbons is the most probable outcome in the mid-to-late 21st century.

TABLE 1. Three scenarios of potential paths for Saudi Arabia's adoption of fusion energy.

Scenario	Fusion Energy Contribution to Grid (%)	Impact on Energy Mix (%)	Numerical Impact on Energy Mix (TWh)
Optimistic Scenario	10–15% by 2045	Hydrocarbons: 40–45%; Renewables: 40–50%; Fusion: 10–15%	Fusion: 50–75 TWh; Renewables: 200–250 TWh; Hydrocarbons: 175–225 TWh
Moderate Scenario	5–10% by 2050	Hydrocarbons: 50%; Renewables: 40–45%; Fusion: 5–10%	Fusion: 25–50 TWh; Renewables: 175–225 TWh; Hydrocarbons: 200–250 TWh
Conservative Scenario	<5% by 2060	Hydrocarbons: 55–60%; Renewables: 40–45%; Fusion: <5%	Fusion: <25 TWh; Renewables: 175–225 TWh; Hydrocarbons: 275–300 TWh

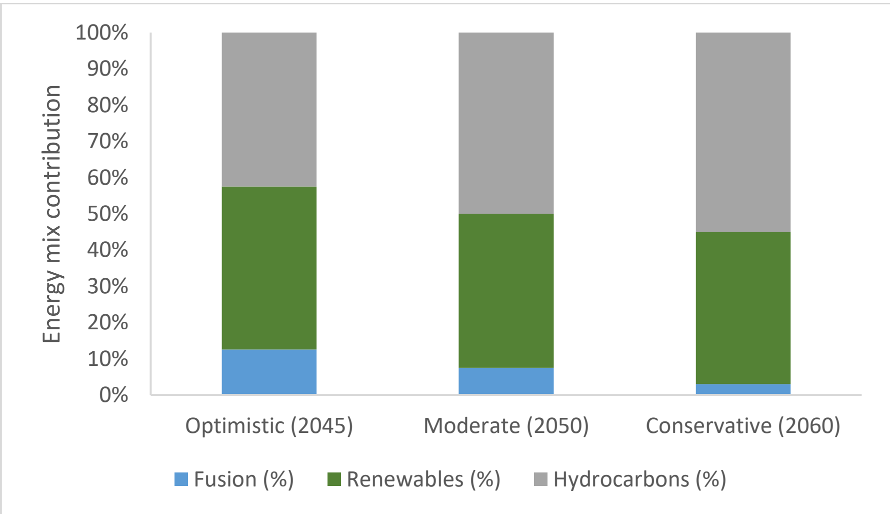

FIG. 4. Energy mix contribution (%) for three scenarios in Saudi Arabia.

4. CONCLUSION

This study provides a comprehensive evaluation of the potential adoption of fusion energy in Saudi Arabia, considering technological readiness, economic viability, and policy implications. By analyzing multiple future scenarios, the research highlights the transformative potential of fusion energy in reducing reliance on hydrocarbons and supporting a clean energy transition.

Under an optimistic trajectory, fusion energy could account for up to 15% of the national electricity grid by 2045, contributing up to 75 TWh of power annually. Even a conservative estimate of 5% by 2060 would mark a significant diversification in Saudi Arabia's energy portfolio. Economically, the shift toward fusion energy could create numerous jobs in high-tech sectors, reduce vulnerability to oil price fluctuations, and enhance long-term energy security. However, the high initial costs and the prolonged development timeline remain substantial barriers. To accelerate adoption, Saudi Arabia must engage in global fusion collaborations such as ITER, develop local expertise through educational initiatives, and establish favorable regulatory policies to attract private-sector investment. Investments in energy storage and smart grid technologies will also be critical to ensure seamless integration of fusion with renewables. While full-scale commercial fusion power remains at least two decades away, Saudi Arabia's strategic positioning, financial resources, and commitment to sustainability make it a strong candidate for early adoption.

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