

Charting the Future of Nuclear Energy Roadmaps for Fission and Fusion Technologies

Farhang Mossavar-Rahmani¹ and Bahman Zohuri²

1. School of Business Technology and Engineering, National University, San Diego 92110, California, USA

2. Ageno School of Business, Golden Gate University, San Francisco 94105, California, USA

Abstract: As the world faces increasing energy demands and concerns about climate change, nuclear power is experiencing a resurgence as a viable and sustainable energy source. This article explores the strategic initiatives concerning the advancement of nuclear technologies, highlighting the prompt adoption of SMRs (small modular reactors), the ongoing advancements in Generation IV reactors in the medium term, and the long-term aspirations linked to nuclear fusion. SMRs offer enhanced safety, economic viability, and flexible deployment alternatives, making them an attractive solution for meeting pressing energy demands. In the medium term, Generation IV reactors are anticipated to improve efficiency, sustainability, and safety, effectively tackling the challenges associated with conventional fission reactors. However, significant challenges lie ahead, including public perception, regulatory hurdles, financial barriers, and the need for a skilled workforce. By addressing these challenges, nuclear power can play a pivotal role in creating a sustainable and reliable energy future, contributing significantly to global efforts in climate change mitigation.

Key words: Nuclear power, SMRs, Generation IV reactors, nuclear fusion, sustainability, climate change, energy demand, public perception, regulatory framework, workforce development.

1. Introduction

As of 2019, approximately 450 nuclear reactors were operational across 31 nations. Nuclear energy accounts for over half of the electricity production in certain countries, such as Slovakia, France, Hungary, and Ukraine. Nevertheless, significant incidents like Fukushima, Chernobyl, and Three Mile Island have hindered the growth of the nuclear sector.

Nuclear power is experiencing a revival in light of the global challenges posed by climate change and the pressing demand for sustainable energy solutions.

Governments and private entities worldwide are reassessing the significance of nuclear energy within their energy strategies. This article delves into the pathways toward new nuclear technologies, emphasizing developments in SMRs (small modular reactors), Generation IV fission reactors, and the promising area of nuclear fusion. We can better understand how these innovations may contribute to a sustainable energy

future by analyzing the short-, medium-, and long-term prospects.

Current nuclear reactors utilize fission, a well-established technology that has been in use for many years. Despite its drawbacks, such as the generation of long-lasting radioactive waste, fission remains a viable option for producing carbon-free electricity. Companies like General Electric Vernova's BWRX-300 and TerraPower's Natrium are actively developing next-generation reactors that promise enhanced safety and efficiency, thereby continuing to serve as significant sources of carbon-free energy.

Simultaneously, the potential of "Fusion Energy" is being explored through two distinct methodologies: MFC (magnetic fusion confinement) and IFC (inertial fusion confinement), as illustrated in Figs. 1 and 2, respectively. These efforts are being pursued by scientists and engineers around the globe.

Fusion, the process that fuels the sun, has been a

Corresponding author: Bahman Zohuri, Ph.D., adjunct professor, research field: electrical and computer engineering.

focus of research since the 1920s, yet we have not yet achieved practical implementation. Nevertheless, the advancements made in this field are noteworthy.

Fusion has the potential to generate four times the energy produced by fission and nearly four million times more energy than the combustion of coal or gas.

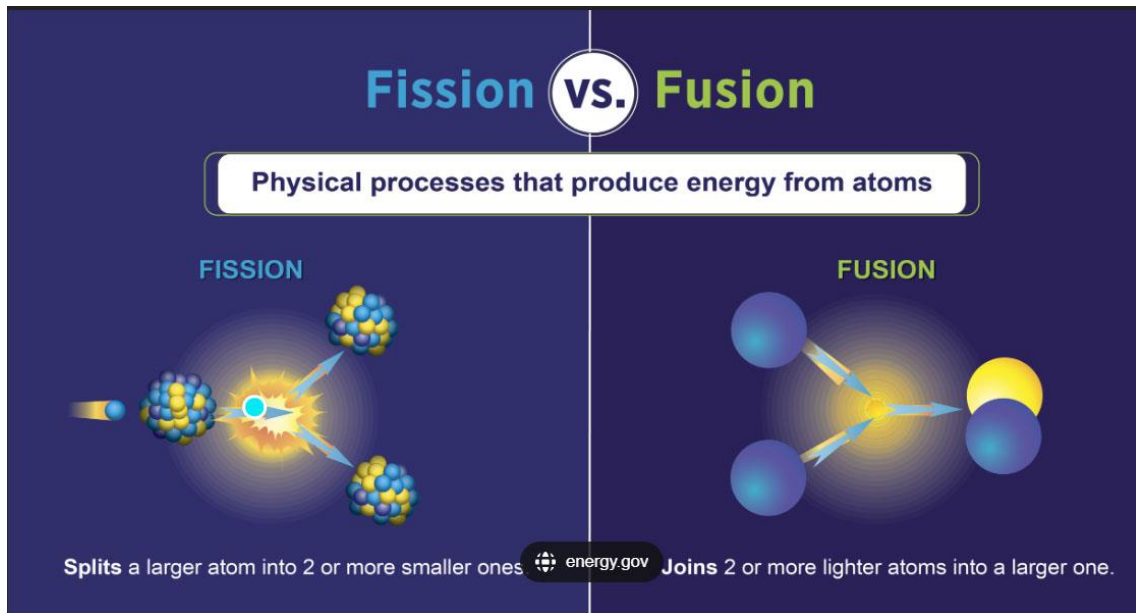


Fig. 1 Physical processes driven by fission vs. fusion.
Source: www.energy.gov.

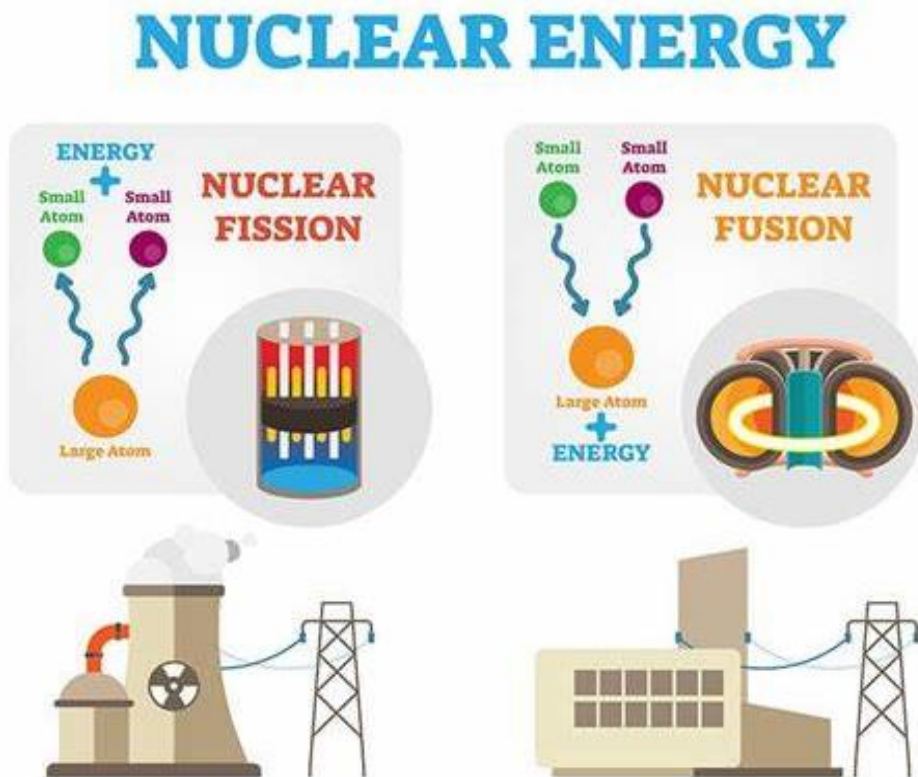


Fig. 2 Ongoing research of the future clean energy.
Source: <https://www.theecoexperts.co.uk/>.

2. The Challenges ahead

To harness the full potential of emerging nuclear power, several challenges must be addressed despite the promising advancements in nuclear technology. A significant barrier remains the public's perception of nuclear energy and its associated risks, primarily influenced by historical incidents that have instilled fear regarding technology. Building trust through transparent communication and active community engagement will be crucial in alleviating this apprehension. Additionally, regulatory frameworks must evolve to accommodate the innovative designs of Generation IV reactors and SMRs, all while ensuring environmental protection and safety are upheld [1].

Economic challenges also arise due to the need for significant funding for research, development, and the actual implementation of these technologies, particularly fusion, which is still in the trial phase. Additionally, the successful implementation and operation of advanced nuclear technologies rely heavily on a skilled workforce, necessitating comprehensive training initiatives to equip the next generation of technicians and engineers. Numerous problems need to be addressed to fully harness the potential of nuclear power in the worldwide energy landscape.

Moreover, the government's involvement is essential, as government backing is vital for the progress of both fission and fusion technologies. Collaborations between the public and private sectors could be instrumental in pushing these technologies forward.

3. Near-Term Developments: SMRs

In the near term, the focus is primarily on the deployment of SMRs. These compact and scalable reactors offer several advantages over traditional large reactors.

3.1 Enhanced Safety

SMRs are designed with advanced safety features

that minimize the risk of catastrophic failures, making them an attractive option for regions wary of nuclear power.

3.2 Cost-Effectiveness

With reduced initial capital expenses and shorter construction timelines, SMRs are more attainable for utility companies and can be developed incrementally to accommodate demand.

3.3 Flexible Deployment

SMRs can be located in areas that are not suitable for large reactors, offering energy access to remote regions and fostering regional energy independence.

Countries like the United States, Canada, and the United Kingdom are leading the charge in SMR development, with various designs under consideration, such as NuScale Power's SMR and the Canadian Nuclear Safety Commission's regulatory framework for new technologies. As these projects move from concept to reality, they will play a crucial role in the immediate energy landscape [1].

4. Mid-Term Prospects: Generation IV Reactors

Looking further ahead, Generation IV reactors promise significant advancements in nuclear technology. These reactors aim to provide sustainable and efficient energy generation while addressing the concerns associated with conventional fission reactors.

4.1 Increased Efficiency

Generation IV reactors are designed to operate at higher temperatures and utilize fuels more effectively, resulting in less waste and improved energy output.

4.2 Sustainability

With innovations such as fast neutron reactors and molten salt reactors, Generation IV designs can recycle nuclear fuel and reduce the long-term radiotoxicity of nuclear waste.

4.3 Enhanced Safety and Security

These reactors incorporate passive safety systems that automatically shut down without human intervention, making them inherently safer.

Countries such as France, Japan, and China are investing heavily in research and development for Generation IV technologies. The deployment of these reactors in the mid-term could help transition nuclear power into a more sustainable and accepted energy source [2-4].

5. Far-Term Aspirations: Nuclear Fusion

The far-term future of nuclear power may lie in nuclear fusion. This technology promises a nearly limitless energy source, mimicking the processes that power the sun. Key benefits of fusion include:

5.1 Abundant Fuel Supply

Fusion relies on isotopes like deuterium and tritium, which are abundant in seawater and lithium, ensuring a

virtually inexhaustible supply of fuel.

5.2 Minimal Waste

Fusion produces significantly less radioactive waste compared to fission, and the waste it produces has a much shorter half-life.

5.3 Safety

Fusion reactions require precise conditions to occur; if containment fails, the reaction stops, eliminating the risk of a meltdown.

Despite these advantages, nuclear fusion remains in the experimental stage. Projects like ITER (international thermonuclear experimental reactor) (i.e., Fig. 3) in France are crucial for advancing fusion technology, hoping to achieve net positive energy output in the coming decades. See Fig. 4 that is a presentation of timeline of fusion technology. As research continues, fusion could become a cornerstone of the global energy mix by the end of the century [5, 6].

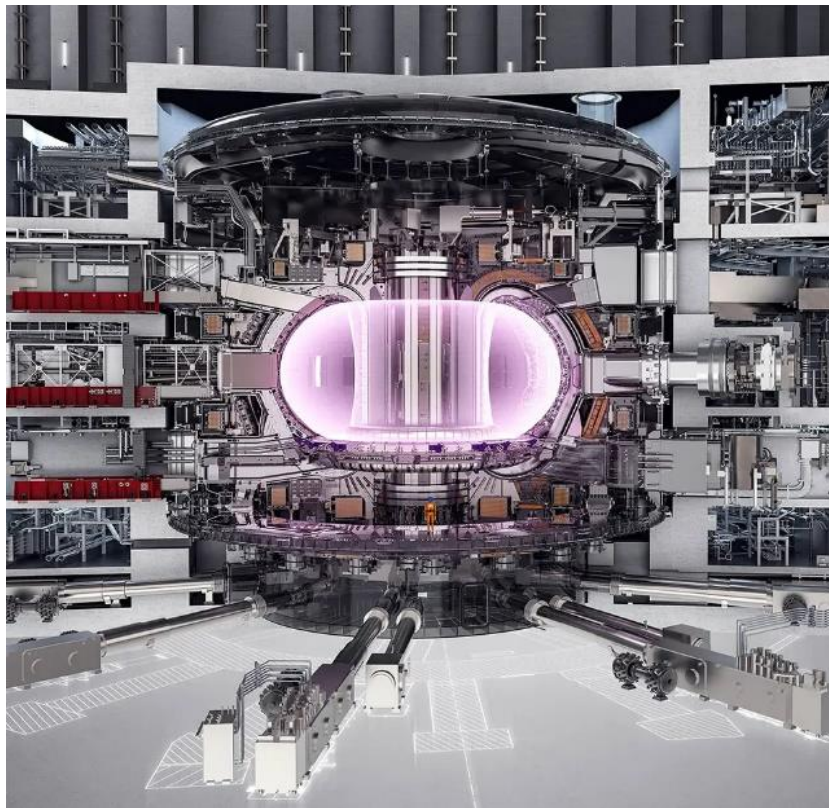


Fig. 3 ITER fusion reactor is 50% complete.

Source: Futuretimeline.net.

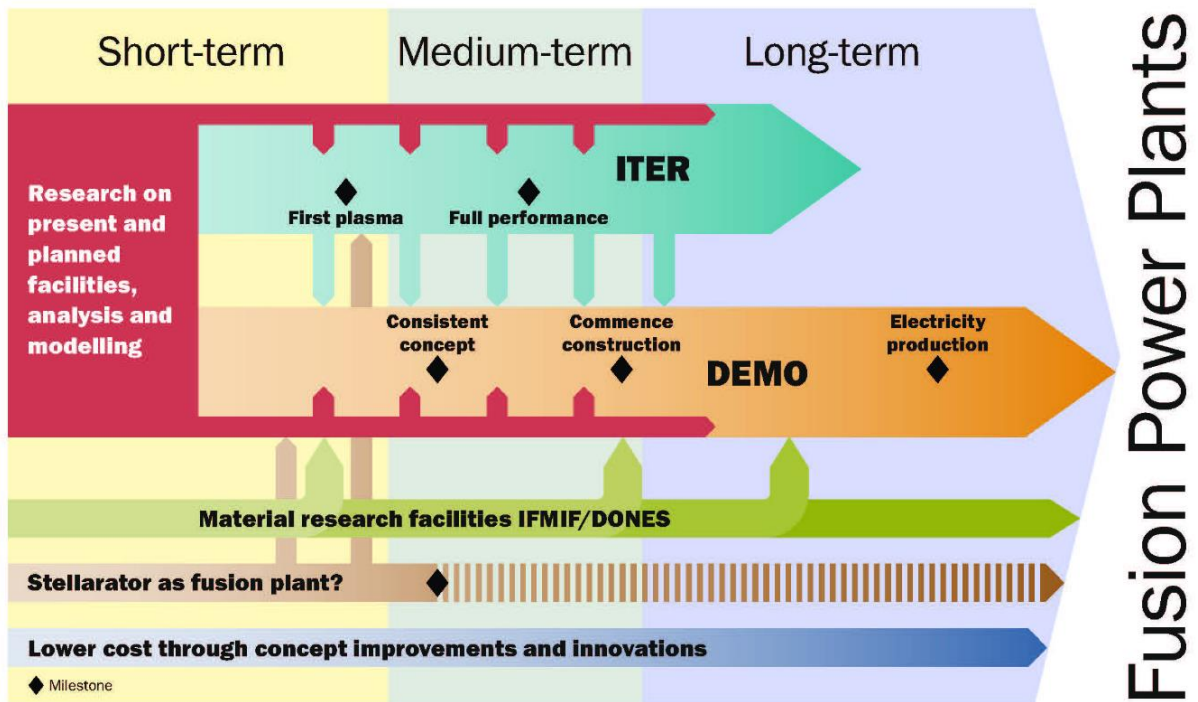


Fig. 4 Nuclear fusion power plant diagram.

Source: ar.inspiredpencil.com.

6. Conclusion

Nuclear energy's future is bright, with the potential for significant advancements in fission technologies. However, it is the promise of fusion technology that truly excites us. The political will to fund these projects is not just important, it is crucial. As citizens, we have the power to influence this will. Let us keep a close eye on this area, as the next major energy revolution could be just around the corner, waiting for our support!

The global push for nuclear power is multifaceted, encompassing the near-term rollout of SMRs, the mid-term advancements of Generation IV reactors, and the long-term potential of nuclear fusion. Each pathway presents unique challenges and opportunities, but they all contribute to a shared goal: a sustainable and reliable energy future. As nations collaborate and innovate in this field, nuclear power can be pivotal in addressing

climate change and meeting the world's energy demands.

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