Ana Belen Rivera Lona

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Nuclear Fusion: The Paradox of Potential

As Earth's population approaches its limits, the demand for energy that is likewise increasing is understandable. To keep up with these needs, we must find a reliable and innovative energy source. The discovery of fossil fuel has led to many technological advances thanks to the energy provided, but it is, in the end, a non-renewable resource. It will completely deplete at some point. At the same time, several types of renewable energy like solar, wind, and hydropower became widely used. However, these energy sources produce their own issues such as intermittency and land use.This is where nuclear energy stands out. Nuclear fission is already fairly widespread, but a similar source of energy–an even newer, safer, and uncertain one–exists. Nuclear fusion has become a major discussion topic, often called the "holy grail" of energy. It can provide for thousands of years with minimal environmental impact. Fusion promises a full on energetic utopia. However, despite the recent milestones of nuclear fusion, there are still remaining obstacles. There remains work on the possible solution to the looming energy crisis in coming decades.

Fusion energy, which powers stars like our sun, requires the union of light elements, typically isotopes of hydrogen, to form heavier elements, such as helium. This process releases massive amounts of energy. However, recreating these conditions on Earth is extraordinarily difficult, as it requires temperatures exceeding 150 million degrees Celsius—about ten times hotter than the sun's core—and the ability to confine this plasma without it touching the reactor walls (Tokimatsu et al., 2003, p. 776). Achieving these conditions is the central challenge of fusion energy. Recent years have seen significant advancements toward overcoming these problems. One of the most notable achievements happened in December 2022, when the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory achieved a net energy gain—the first time in history that more energy was produced than consumed in a fusion reaction—inputting 2 megajoules (MJ) and generating 3.15 MJ of energy (Sadik-Zada et al., 2024, p. 3). This breakthrough demonstrated that fusion energy is no longer just a theoretical concept but could be a viable energy source in the future. At the same time, large-scale international collaborations like the ITER (International Thermonuclear Experimental Reactor) project continue to make progress toward achieving sustained fusion. ITER, located in France but collaborating with several countries, aims to demonstrate the feasibility of producing net energy through fusion by the mid-2030s, with the ultimate goal of creating a prototype commercial fusion reactor, DEMO, by the end of the century (Lee & Saw, 2011, p. 402). These projects are milestones in the journey to commercial fusion energy, each contributing to the knowledge and technology needed for large-scale fusion power plants as well as allowing a clearer timeline for nuclear fusion.

Fusion research is progressing, but the timeline for a fully functional fusion power plant is still decades away. Initially, it was predicted that fusion would be ready by the early 21st century. However, over the past 60 years, that timeline has shifted as the challenges associated with achieving stable fusion have proven more difficult than anticipated (Rose, 1968, p. 3). While ITER is scheduled to demonstrate sustained fusion reactions in the 2030s, commercial fusion reactors like DEMO are not expected to be ready until the 2050s or even 2100 (Lee & Saw, 2011, p. 402). The financial costs of developing fusion energy are of higher importance for the whole success of the energy source. ITER alone is estimated to cost over $20 billion, and the subsequent stages of development will require hundreds of billions more (Lopes Cardozo et al., 2015, p. 98). This stands in contrast to the costs of renewable technologies, like solar and wind, given nuclear fusion seems to be lagging 50 years behind in development (Lopes Cardozo et al., 2015, p. 99). Fusion is in its exponential growth phase, meaning that for every breakthrough, there must be significant investments, even when the return on investment (ROI) is not yet clear (Lopes Cardozo et al., 2015, p. 97). This phase is expected to last decades, which raises the question: is nuclear fusion as an energy source worth it? Despite these hurdles, the potential payoff is enormous. Fusion energy could eventually provide virtually limitless power with greatly limited greenhouse gas emissions, making it a crucial tool in combating climate change. If fusion is successful, it could completely transform the energy landscape, providing a solution to the world's growing energy needs while mitigating the environmental damage caused by fossil fuels.

While nuclear fusion holds great promise, there are concerns about its feasibility and competition from other renewable energy sources. Nuclear energy is not always very well received. Arthur Turrel, a researcher with a PhD in Plasma Physics from the Imperial College of London wrote in his book *The Star Builders: Nuclear Fusion and the Race to Power the Planet,* "When a technology involves 'nuclear' anything you may find yourself getting a frosty reception. […] Most commonly, it's associated with nuclear fission power, which divides opinion and produces radioactive waste that we'll have to store for thousands of years" (Sadik-Zada et al., 2024, p. 7). It's important to understand the main concerns of fusion and to separate them from nuclear fission, given they are very separate processes. One key concern is whether fusion will ever be commercially viable. Many argue that the immense cost of just building and materials makes fusion an unrealistic solution compared to rapidly advancing solar and wind technologies. In addition, fusion's timeline for large-scale energy production is uncertain, whereas solar and wind have already reached maturity and are being deployed at scale worldwide. However, fusion offers several distinct advantages over these existing technologies. Unlike solar and wind, which are intermittent and require vast amounts of land to generate significant power, fusion would provide continuous power with much less land use (Sadik-Zada et al., 2024, p. 7). While wind turbines require thousands of acres to generate the same amount of energy as a fusion reactor, a fusion plant could produce power in a much smaller footprint, making it a more efficient solution in densely populated areas. Not only by contributing in reducing the amount of space employed, making way for the population, but it provides the large amount of energy needed for these densely populated areas. Moreover, fusion has a clear advantage over nuclear fission in terms of safety and waste. Fusion reactions do not produce the same highly radioactive waste as fission reactors–such as plutonium which has a half life of more than 24 thousand years–and any waste generated from fusion decays in a fraction of the time (Sadik-Zada et al., 2024, p. 6). Additionally, fusion reactors do not have the possibility of meltdowns like fission reactors. Fusion reactions are not chain reactions so if a factor is removed, the process would just stop and the plasma would cool down. Meltdowns have been a major concern after disasters like those of Fukushima and Chernobyl (Sadik-Zada et al., 2024, p. 6).

Nuclear fusion represents humanity's greatest opportunity to achieve a sustainable, clean, and arguably limitless energy source. While some question its feasibility and argue that it may never catch up to existing renewables, fusion's unmatched potential for efficiency and environmental safety makes it worth the investment. It is important to recognize that humanity has already achieved controlled fusion for destructive purposes. The hydrogen bomb—a fusion reaction triggered by a fission reaction—demonstrates that we have achieved controlled nuclear fusion under specific conditions, although with devastating consequences (Bethe, 1950). If we can master fusion for war, it is possible to master it for peace. The technical knowledge required to create a hydrogen bomb was once considered unconquerable, yet humanity achieved it. Similarly, the challenge of harnessing fusion for energy is not beyond our reach—it simply requires time, investment, and collaboration. The hydrogen bomb is a dystopian symbol of our capacity for destruction; nuclear fusion energy is a utopian vision of what we can achieve when we unite science and humanity's best interests.

References

Bethe, H. A. (1950). The hydrogen bomb. *Bulletin of the Atomic Scientists*, *6*(4), 99-104. https://doi.org/10.1080/00963402.1950.11461231

Lee, S., & Saw, S. H. (2011). Nuclear fusion energy—mankind's giant step forward. *Journal of Fusion Energy*, *30*(5), 398-403. https://doi.org/10.1007/s10894-011-9390-7

Lopes Cardozo, N. J., Lange, A. G. G., & Kramer, G. J. (2015). Fusion: Expensive and taking forever? *Journal of Fusion Energy*, *35*(1), 94-101. https://doi.org/10.1007/s10894-015-0012-7

Rose, D. J. (1968, January 1). *FEASIBILITY OF POWER BY NUCLEAR FUSION*. Office of Scientific and Technical Information (OSTI). https://doi.org/10.2172/4513744

Sadik-Zada, E. R., Gatto, A., & Weißnicht, Y. (2024). Back to the future: Revisiting the perspectives on nuclear fusion and juxtaposition to existing energy sources. *Energy*, *290*, 129150. https://doi.org/10.1016/j.energy.2023.129150

Tokimatsu, K., Fujino, J., Konishi, S., Ogawa, Y., & Yamaji, K. (2003). Role of nuclear fusion in future energy systems and the environment under future uncertainties. *Energy Policy*, *31*(8), 775-797. https://doi.org/10.1016/s0301-4215(02)00127-1