THE ROLE OF FUSION ENERGY IN FUTURE ENERGY SCENARIOS

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RESUMEN

El Consorcio Europeo para el Desarrollo de la Energía de Fusión (EUROfusion) apoya la investigación socioeconómica para evaluar la viabilidad y competitividad de la fusión nuclear dentro de un marco energético global bajo en carbono. Este estudio explora las posibles contribuciones de la fusión a los sistemas energéticos futuros utilizando el Sistema Integrado MARKAL-EFOM (TIMES) y el Modelo EUROfusion TIMES (ETM), que abarca 17 regiones globales y una base de datos rica en tecnología con más de mil tecnologías energéticas. Analizamos 25 escenarios, diferenciando la disponibilidad de la fusión (temprana o tardía), la tasa de difusión, las restricciones de energías renovables variables (vREN) y la sensibilidad a los costos de la fusión. Los resultados indican que la fusión podría alcanzar una participación significativa en la producción de electricidad, especialmente en condiciones de disponibilidad temprana y despliegue rápido, llegando hasta un 22% para el año 2100 en escenarios óptimos. En contraste, una difusión más lenta o una penetración no restringida de vREN reduce el papel de la fusión. Además, la adopción de la fusión permite una mayor electrificación, desplazando tecnologías fósiles de Captura y Almacenamiento de Carbono (CCS) y algunas renovables. La adopción regional varía, con una adopción temprana en regiones tecnológicamente avanzadas como China, India y Estados Unidos, mientras que otras regiones, incluyendo Europa, comienzan más tarde debido a factores económicos y técnicos. Los hallazgos enfatizan la importancia de la preparación tecnológica, la aceptación social y la disponibilidad de materiales, particularmente el tritio, en la determinación del potencial de la fusión.

Palabras clave: fusión nuclear, modelado de sistemas energéticos, sistemas energéticos bajos en carbono, impacto socioeconómico, integración de energías renovables, escenarios de políticas energéticas.

ABSTRACT
The European Consortium for the Development of Fusion Energy (EUROfusion) supports socio-economic research to assess the viability and competitiveness of nuclear fusion within a low-carbon global energy framework. This study explores fusion's potential contributions to future energy systems using The Integrated MARKAL-EFOM System (TIMES) and the EUROfusion TIMES Model (ETM), which incorporates 17 global regions and a technology-rich database of over one thousand energy technologies. We analyze 25 scenarios, differentiating fusion availability (early or late), diffusion rate, variable renewable energy (vREN) restrictions, and sensitivity to fusion costs. Results indicate that fusion could achieve significant electricity production shares, especially under conditions of early availability and rapid deployment, reaching up to 22% by 2100 in optimal scenarios. In contrast, slower diffusion or unrestricted vREN penetration reduces fusion's role. Additionally, fusion's adoption enables greater electrification, displacing fossil Carbon Capture and Strorage technologies (CCS) and some renewables. Regional uptake varies, with early adoption in technologically advanced regions like China, India, and the USA, while other regions, including Europe, begin later due to economic and technical factors. Findings emphasize the importance of technological readiness, societal acceptance, and material availability, particularly tritium, in determining fusion's potential.

Key words: nuclear fusion, energy system modelling, low-carbon energy systems, socio-economic impact, renewable energy integration, energy policy scenarios.

1. INTRODUCTION

The European Consortium for the Development of Fusion Energy (EUROfusion) has promoted socio-economic studies on fusion to investigate the social acceptability and the economic competitiveness of fusion power plants in a future energy market.
Nuclear fusion will appear in the context of increasing energy demand due to the continuous population growth, decreasing renewable energy costs and the change in societies' energy-related behaviours together with an evident climate change. Fusion presents a good opportunity to produce a lot of energy while avoiding greenhouse gas (GHG) emissions.
The development of alternative energy system outlooks is the main tool to explore options for the future. A well-assessed model generator, The Integrated MARKAL-EFOM System (TIMES), is used to create the worldwide energy system model and look at its possible evolution according to different energy and environmental policies. Using this model, we analyse the contribution of fusion power to a future low-carbon global electricity system.

2. METODOLOGY

The TIMES model generator was developed as part of the IEA-ETSAP (Energy Technology Systems Analysis Program), an international community which uses

long-term energy scenarios to conduct in-depth energy and environmental analyses (Loulou et al., 2004).
The TIMES model generator combines two different, but complementary, systematic approaches to modelling energy: technical engineering approach and economic approach.
TIME's characteristics: technology-rich, bottom-up model generator, uses linear programming to produce a least-cost energy system, optimized according to several user constraints, typically for medium to long-term time horizons. Different scenarios can be built following different storylines, modifying uncertainties or driving forces like social dynamics toward transformation, innovation, geopolitical instability, policies or economic factors.

The EUROfusion TIMES Model (ETM) has a global resolution distributed in 17 regions. ETM is a technology-rich model consisting of a large techno-economic database with more than one thousand energy technologies for all the demand (residential, commercial, transport, industry and agriculture) and supply (power and heat generation and upstream) sectors. In ETM fusion technology is considered as an energy source alternative for future energy systems.
Two alternative fusion plants are considered based on the work done in EUROfusion (PPCS and DEMO): basic power plant and advanced power plant. The costs currently used in ETM are desired targets rather than estimates

Data for the fusion technologies.

	Date	Specific capital ($\$_{2005}$/kW)	Efficiency (%)	FIXOM (M$\$_{2005}$/GWa)	VAROM (M$\$_{2005}$/PJ)
Basic plant	2050	5910	42	65.8	2.16
	2060	4425	42	65.8	1.64
Advanced plant	2070	4220	60	65.3	2.14
	2080	3255	60	65.3	1.64

Table 1: Nuclear fusion costs. Source: Cabal et al., 2017.

The root scenario is aligned with the The Intergovernmental Panel on Climate Change (IPCC) Shared Socioeconomic Pathways (SSP2), a “middle of the road” climate change scenario. We have selected the 2.6 RCP. Then, we distinguish alternatives for:

- Fusion availability horizon (Early 2035 and Late 2070)
- Fusion deployment rate (Fast and Slow) based on Tritium availability for start-up
- Technical restriction on variable renewable electricity deployment (restriction on vREN penetration and No restriction)
- Sensitivity on fusion costs (Low (*0.6), Reference and High (*1.2))

Creating 25 different scenarios including a scenario without fusion presence (S25)

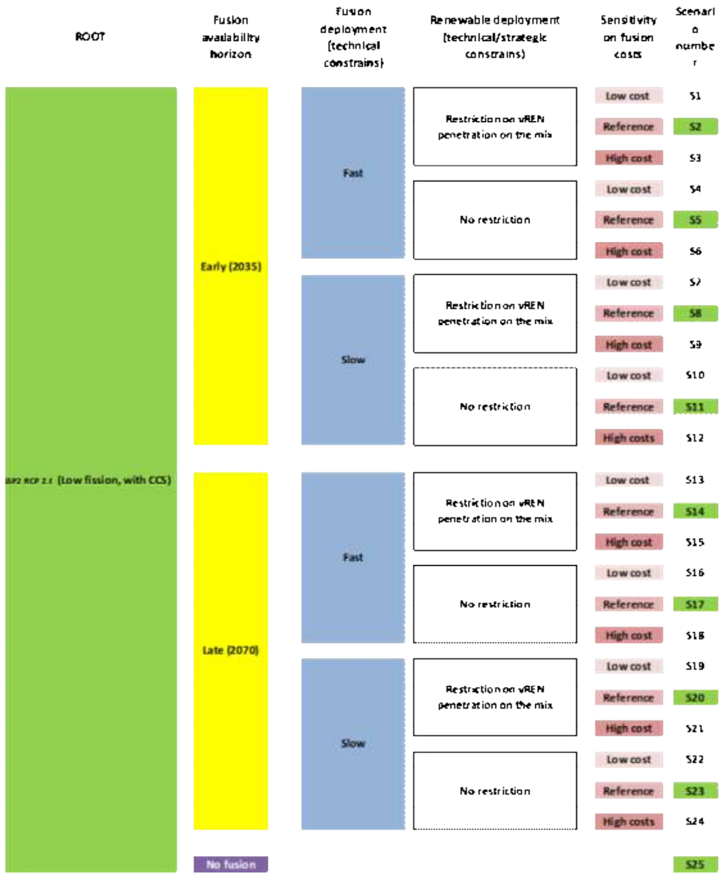

Fig. 1: Scenario tree. Source: Author

3. RESULTS

In all scenarios, the system evolves towards one dominated by renewables, especially solar PV and to a lesser extent wind, and nuclear technologies, including fission and fusion.

The maximum fusion penetration occurs in scenario S02 (early availability and fast diffusion of the fusion technology with restriction on vRES penetration) where it represents 22% of total electricity production in 2100. The minimum deployment of the technology occurs in scenario S23 (late availability and slow diffusion of the fusion technology with no restriction on vRES penetration).

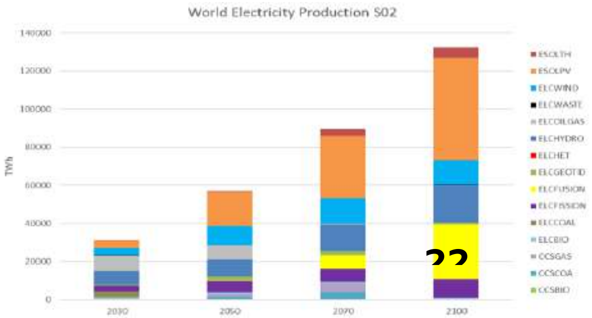

Fig. 2: World Electricity Production scenario S02. Source: Author

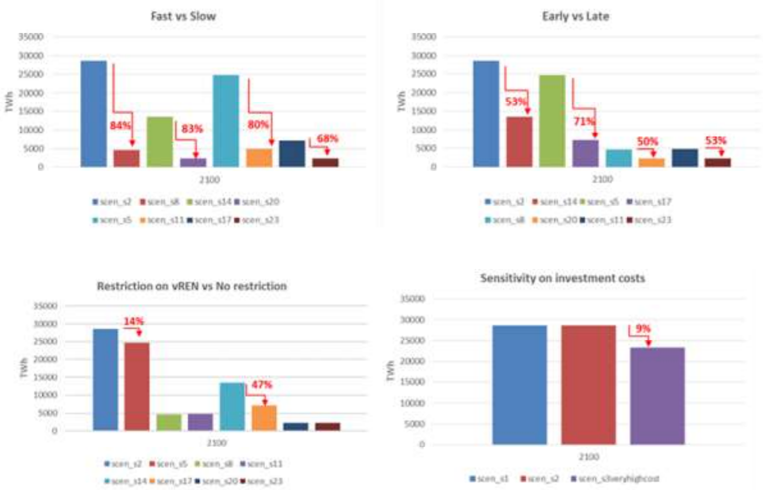

Fig. 3: Role of sensitivity parameters in fusion electricity production in 2100. Source: Author

In all scenarios, fusion enters the system shortly after it becomes commercially available, but its role is very sensitive to the factors analysed, in particular the speed of diffusion (fast or slow) and the time when it is expected to be available (early or late).

Technical constraints on the share of variable renewables (solar PV and wind) seem to play a role only in the scenarios with fast diffusion of fusion technology.

On the contrary, the investment cost of the fusion reactor is not a relevant factor for the expected share of the technology at the end of the century. Only a very strong increase in capital costs (*1.75) will reduce the penetration of fusion by 9%.

The availability of fusion allows for higher electricity production and thus higher electrification of the energy system. The technologies that are somehow displaced by fusion penetration, according to these results, are first fossil CCS technologies and then some renewables such as wind, solar PV and other renewables.

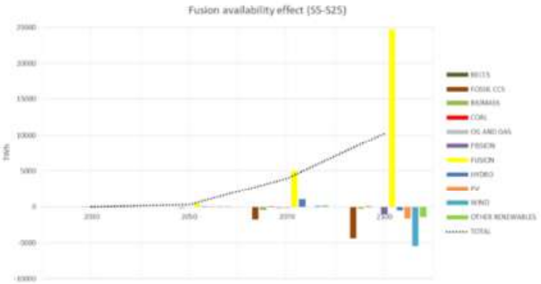

Fig. 4: Role of sensitivity parameters in fusion electricity production in 2100.
Source: Author

Some regions will start using fusion technology as soon as it becomes available. This is the case for China, India and the USA. Other regions start using fusion in 2070, such as Africa, Australia, the Middle East, Mexico, South Korea and other countries in Asia.

Europe starts to use fusion in 2080, waiting for the advanced technology to become available. In S2 and S5 the penetration of fusion is quite significant, reaching 42% and 46% respectively.

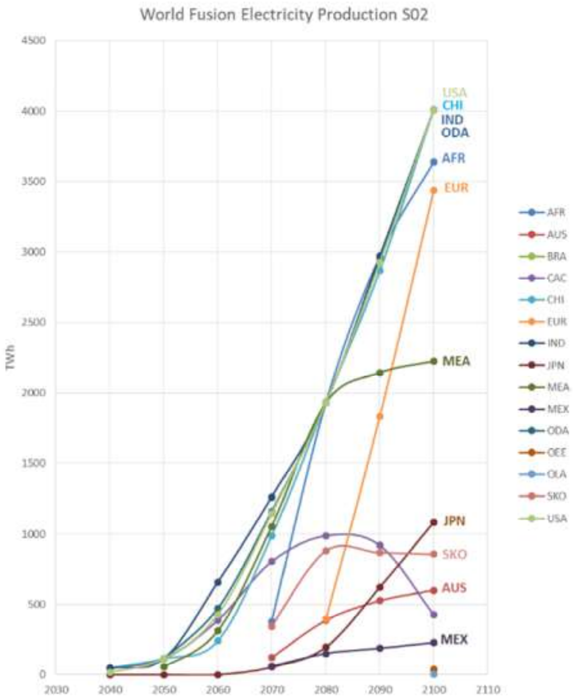

Fig. 5: Fusion electricity production in the different regions in scenario.

4. DISCUSSION

This study offers a detailed exploration of nuclear fusion's potential role in a future low-carbon global energy system, assessing its competitiveness and societal acceptance through various scenarios. By utilizing the TIMES model and the ETM database, which incorporates numerous socio-economic and technical variables, the analysis demonstrates the complex, dynamic interactions between fusion power, renewable energy sources, and fossil-based technologies under different policy, technological, and economic assumptions. Several critical insights emerge from the findings, which are essential for both policymakers and energy researchers.

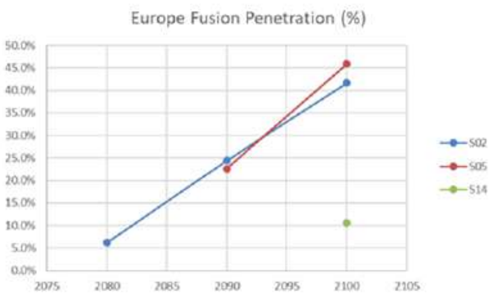

Fig. 6: Fusion electricity penetration in Europe. Source: Author

One key takeaway is that fusion technology, though potentially transformative, faces substantial variability in its projected role depending on availability timelines and deployment rates. Scenarios with early availability and fast diffusion of fusion indicate the highest penetration, reaching up to 22% of total electricity production by 2100 in the most favourable conditions. This outcome highlights fusion's capacity to complement renewable energy sources and achieve high levels of system decarbonisation, especially when certain restrictions limit variable renewable energy (vREN) contributions. In scenarios where these restrictions are absent, however, renewables such as solar PV and wind become dominant, pushing fusion to a more supplementary role.

The analysis also reveals that fusion technology can support higher electrification levels by displacing fossil-based carbon capture and storage (CCS) technologies, indicating that fusion could reduce dependency on carbon-intensive resources in favor of cleaner electricity. This impact on fossil CCS is a pivotal finding, as it suggests fusion's potential to accelerate fossil fuel phase-out within a diverse energy portfolio, even as it balances against intermittent renewables.

Investment costs in fusion appear to have minimal impact on its penetration except under scenarios with significantly increased capital costs. This suggests that financial barriers alone may not be decisive, but rather the technical readiness, societal acceptance, and availability of crucial materials like tritium play more crucial roles in its uptake. For instance, the diffusion rate of fusion technology is closely tied to tritium availability, underscoring the need for ongoing research and resource planning to support fusion scalability.

The geographical differentiation in fusion adoption timing provides an important perspective on global energy equity. While fusion deployment begins in technologically advanced and resource-rich regions like China, India, and the USA in the early stages, less-developed regions such as Africa and the Middle East are projected to adopt fusion much later. This disparity could have far-reaching implications for global energy security and equitable access to low-carbon energy solutions.

Overall, this study underscores that fusion power, if integrated into the energy system effectively, could play a significant role in the future energy mix. However, realizing its potential will require a nuanced understanding of the timing, technological readiness, societal acceptance, and cross-regional equity in deployment. Addressing these factors thoughtfully can help shape energy policy and investment strategies that maximize fusion's role in achieving a sustainable and low-carbon future.

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