Exploration of Fusion Power Penetration under Different Global Energy Scenarios Using the EFDA Times Energy Optimisation Model

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Abstract. The first commercial fusion power plants are expected to start operating from 2050. How the global energy system will be as for that time nobody knows, but future can be explored by means of scenarios. In this work, several scenarios have been formulated and represented by the EFDA Times model (ETM), a global optimization energy model developed within the framework of the Socio Economic Research of Fusion project (SERF) in EFDA. Some analyses on the evolution of the global energy system in the long term under different scenarios have been carried out with especial focus on the future role of fusion technologies. Different issues related to fusion development have been analysed for each scenario using the ETM model. Results show that fusion technologies participation in the global electricity system by 2100 goes from 10% to 14% depending on the storyline. Using Paternalism as a Reference scenario, some additional analyses have been done. Preliminary results show that the global rate of fusion technologies growth is 12% per year from 2070 to 2100. Besides, fusion penetration is very sensitive to investment cost variations going from 13% to 42% when investment costs are 30% lower than in the Reference case and from 13% to 1% when those costs are 30% higher. Regarding the hypothetical case of fusion technologies anticipation, at the beginning, the penetration is low and similar in both scenarios, Reference and Anticipation, but at the end of the period it is much higher in Anticipation, mainly due to the advanced reactors penetration. Finally, sensitivity analyses have been performed on key parameters such as the discount rate of each technology. The results show that the lower the discount rate, the higher the share of fusion in the global electricity system.

1. Introduction

Within the activities of the former European Fusion Development Agreement (EFDA), the Socio Economic Research on Fusion project (SERF), 1997-2014, was aimed to analyse the socioeconomic and environmental aspects of fusion technologies. In a first stage, the direct and external costs of the fusion fuel cycle were estimated, the last using the ExternE methodology developed under the ExternE Project [1]. Results showed that accidents in the construction and decommissioning of the plant are the activities with highest external costs, followed by disposal of waste.

After the evaluation of the externalities [2] [3] [4], SERF focused in the development of a global energy optimization model to analyse the role of fusion in future scenarios. The EFDA Times Model (ETM) belongs to the TIMES model family, which is a model generator developed by the Technology Collaboration Programme (TCP) Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency (IEA). More information available at the ETSAP web site: http://iea-etsap.org/

From 2014, within the framework of EUROFusion, the modelling activities continue under the Socio Economic Studies project (SES). Last work has been focused on defining new storylines on possible world evolutions and analysing the role of fusion under different scenarios as well as carrying out sensitivity analyses on the most relevant parameters influencing fusion technologies penetration in the global system. Preliminary results are presented in this paper.

2. Methodology

The EFDA Times model (ETM) is a global optimization energy model developed within the framework of the Socio Economic Research of Fusion project (SERF) in EFDA. From its beginning in 2004 [5] the model has continuously been updated, improved and used to analyse the introduction and development of fusion technologies in the future global energy system.

ETM is an optimisation model which aims at providing the optimum energy system composition at the minimum cost under different environmental and socioeconomic assumptions.

ETM consists of a database of thousand energy technologies for all the supply (electricity and heat generation, and upstream) and demand (industry, transport, residential, commercial and agriculture) sectors in the energy system, perfectly characterised by their environmental, technical and economic parameters. That is why all TIMES models are called technology rich models and are considered specifically suitable tools for this kind of analysis of complex systems. ETM in particular stands out due to the in depth characterisation of the nuclear fission and fusion fuel cycles.

Two fusion power plants are described in the model, basic and advanced reactor, characterised by the following parameters:

TABLE I: FUSION POWER REACTORS IN ETM.

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

Socioeconomic data have been taken from the EU DEMO Study [6] and increased 50% to incorporate considerable raises in material prices in the last decade.

The description of the energy system in ETM is based on the Reference Energy System concept (RES). The RES is a graph that represents schematically all the technologies and all the flows of energy fed into, and returned from, each technology. FIG.1shows the RES represented on the 17 regions in which the world is divided in ETM. Such a division was recently made to take into account the world current geopolitical situation. Those regions are connected among them by trade relations (fuels, materials ...).

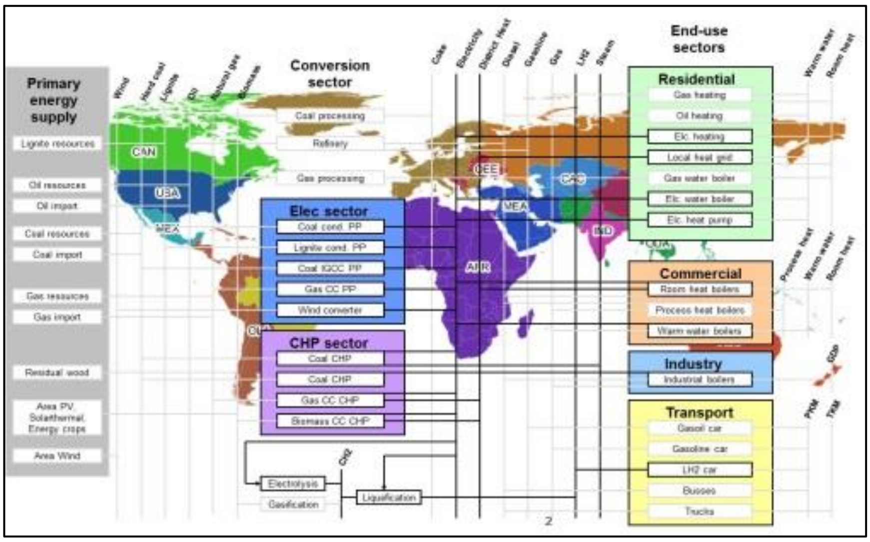

FIG. 1. Reference Energy System in ETM.

Demand projection is endogenously estimated by the model from exogenous socio economic driver projections coming from the general equilibrium model, GEM- E3 [7]. Time horizon chosen is 2100.

3. Storylines and scenarios

After a joint exercise among the project partners, following the methodology described by Ghanadan R. and Koomey J.G. [8], to find key forces in the environment that might influence the penetration of fusion technologies in the global energy system, the main critical factors identified were public acceptance, GDP, technology, climate change and energy costs.

From these results, different future world evolutions were contemplated and consequently, three storylines were formulated:

A. **HARMONY**: A world of strong environmental responsibility shared between energy consumers, and operators take a long-term view when deciding their investments, where a very stringent global carbon emissions target is agreed and different world regions cooperate

B. **PATERNALISM**: A world of mixed environmental responsibility, and operators take a medium-term view when deciding their investments, where a very stringent global carbon emissions target is agreed and different world regions cooperate

C. **FRAGMENTATION/FREE RIDERS**: A world of weak environmental responsibility, and operators take a short-term view when deciding their investments, with a range of regional partial agreements on carbon emissions target and geopolitically constrained energy trade.

These storylines were then translated into scenarios using the following parameters: environmental responsibility was modelled using the elasticity of energy service demands to their drivers in a way that a strong environmental responsibility corresponds to a low elasticity. The term-view taken by operators was modelled using the technology specific hurdle rates so that long-term view corresponds to low rates. Hurdle rate is defined as the minimum return on investment necessary to cover all costs associated with a technology. The riskier the project, the higher the hurdle rate. Finally, global carbon emission targets were set using upper limits according to the Representative Concentration Pathways RCP6 and RCP4.5 [9]. RCP6 and RCP4.5 are scenarios that stabilise radiative forcing at 6 and 4.5 Watts per meter squared in 2100 respectively.

Within these storylines, different scenarios were built. This paper presents the results for the scenarios in TABLE II.

TABLE II: SCENARIOS.

Scenario	**Elasticity**	**Hurdle rate**	**CO2 limit**	**Fusion invest costs**	**Fusion availability**
Harmony	-30% Base	-50% Base	RCP 4.5	Base	Yes
Paternalism	Base	Base	RCP 4.5	Base	Yes
+30%InvCosts	Base	Base	RCP 4.5	+30% Base	Yes
-30%InvCosts	Base	Base	RCP 4.5	-30% Base	Yes
No Availability	Base	Base	RCP 4.5	-	No
Fragmentation	+30% Base	+50% Base	RCP 6	Base	Yes

4. Results

This section presents the results obtained with the ETM for the three main scenarios and the sensitivity analysis on the fusion technologies investment costs. In addition, results from two more studies on fusion rate of growth, and the possibility of fusion not being available in future are shown.

4.1 Fusion penetration in the global electricity system

Fusion technologies penetration has been analysed for the three main scenarios: Harmony, Paternalism and Fragmentation. Results for 2050 and 2100 are shown in FIG. 2.

Fusion technologies participation in the global electricity system by 2100 goes from 10% to 14% depending on the scenario, corresponding the highest penetration to the Harmony scenario, closely followed by the Paternalism scenario. That means that fusion is favoured in a world with a strong environmental responsibility, stringent carbon emissions targets and cooperation among regions. In those scenarios, the electricity system in 2100 is almost decarbonised with a high penetration of renewable and nuclear technologies (75%/20% in Harmony, 64%/22% in Paternalism). In the Fragmentation scenario, there is also a considerable share of Carbon Capture and Storage (CCS) technologies (23%).

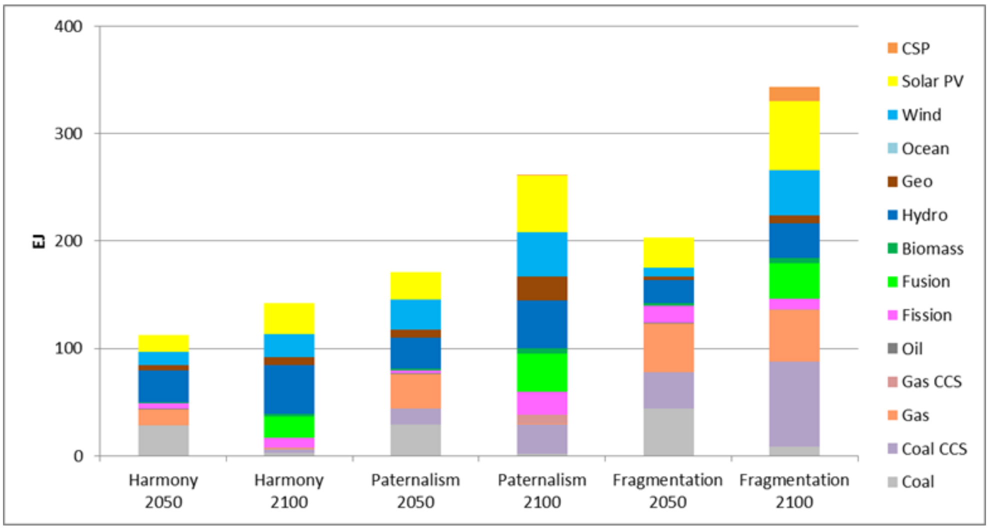

FIG. 2. Future global electricity system under different scenarios.

For the following analyses, Paternalism scenario has been taken as the base one. The rate of growth of fusion technologies in this scenario has been estimated (FIG. 3) resulting in an average 12% per year from 2070 to 2100. Although fusion technologies become available in the system from 2050, real penetration does not start until 2070.

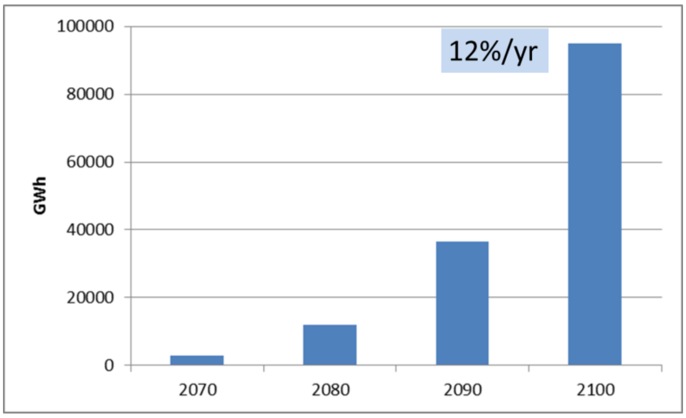

FIG. 3. Rate of growth of fusion technologies.

Also the possibility of fusion technologies not being available in future has been considered and analysed using Paternalism scenario as base case. FIG.4 shows the difference between fusion being or not available. Positive generation represents the increase in production of different technologies to replace the production generated with fusion in the base case. Under this circumstance, most of the electricity generated in 2100 comes from renewable and CCS technologies (68% and 19% respectively). Fusion technologies are mainly replaced by CCS and fission technologies, as can be seen in FIG.4, whose production grows 42% and 37% respectively regarding the base case.

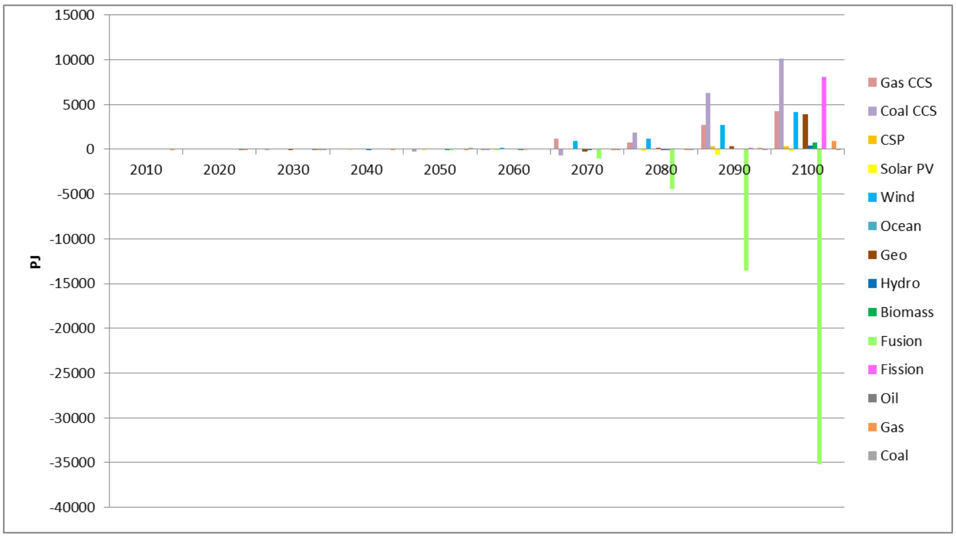

FIG. 4. No fusion technologies availability.

4.2 Sensitivity analysis on costs

A sensitivity analysis on fusion technologies investment costs has been carried out using Paternalism scenario as base case. Results are shown in FIG.5.

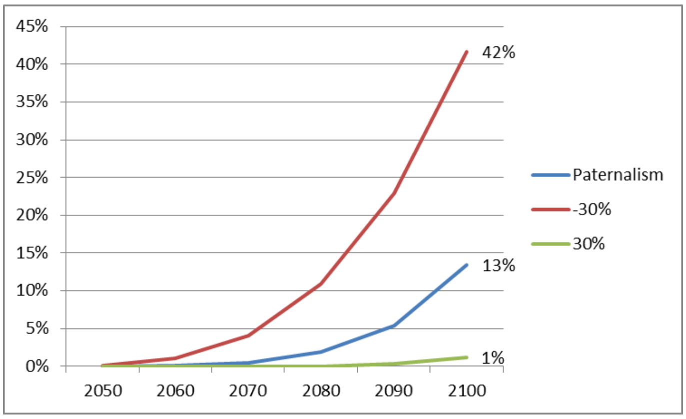

FIG. 5. Sensitivity analysis on costs.

Fusion penetration is very sensitive to investment cost variations going the share in the global electricity system from 13% to 42% when investment costs are 30% lower than in the Paternalism case, and from 13% to 1% when those costs are 30% higher. That shows the relevance of keeping the costs at the level of those in TABLE I or even below because a cost increase higher than 30% may lead fusion to not being part of the electricity system by the end of the century.

5. Conclusions

Optimisation energy models are a suitable prospective tool to approach the future and investigate the role of fusion technologies in the global electricity system. This role may be analysed under different world evolutions, energy and climate policies, and technology developments.

Fusion technologies have an opportunity to participate in the future global electricity system if ambitious environmental targets are set, collaboration among nations works, and costs remain stable.

6. Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the EURATOM research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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