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## Analysis of the potential contribution of fusion power in a future low carbon global electricity system

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### Abstract

Fusion is one of the technologies that may contribute to a future, low carbon, energy supply system and we investigate here the role that it may play. The global energy model EFDA TIMES has been used to analyse how the introduction of fusion interacts with other low carbon technologies in future energy scenarios. First results emphasise the dependence of fusion penetration on investment costs while, in the cases studied, variations of operation and maintenance costs arising from variations in the expected lifetime of replaceable components are not so critical.

Overall in this analysis, fusion contributed to the replacement of fossil fuels, along with fission and renewables. Once the electricity system is carbon free, fusion and fission compete with each other for market share but do not impact strongly on the use of renewable technologies.

### 1. Introduction

The European Fusion Development Agreement (EFDA) has promoted socio-economic research on fusion to investigate both the social acceptability and the economic competitiveness of fusion power plants in a future energy market. It is essential to assess both aspects in order to estimate how likely the involvement of fusion power in a future sustainable energy system is. Nuclear fusion would act in a context of an increasing energy demand due to the continuous population growth and the change in societies energy-related behaviours together with an evident climate change. Fusion presents a good opportunity to produce a large amount of energy while consuming a small amount of fuel, and avoiding greenhouse gases (GHGs) emissions. The technical viability of fusion is still under assessment through the International Thermonuclear Experimental Reactor (ITER) whose construction is on-going. While ITER is being built, the component design and engineering design of the first Demonstration power plant (DEMO) are ongoing activities to be completed by 2030. Nevertheless, taking into account the possible contribution of fusion in a future energy system is far from being premature. The energy system is distinguished by a great inertia therefore the effects of energy policies become tangible in the long term only. For this reason, policies favouring carbon-free energy technologies should be implemented years before the technology is expected to enter the energy market.

The development of alternative energy system outlooks are the main tool to explore options for the future, so a well assessed model generator, TIMES (The Integrated MARKAL-EFOM System), is used to create the worldwide energy system model and look at

its possible evolution according to different energy and environmental policies. This paper mainly focuses on the contribution of fusion power to a future low carbon global electricity system.

## **2. EFDA Times model**

The EFDA TIMES Model (ETM) is an economic model of the global energy system based on the TIMES framework. Its development within the EFDA-SERF project (Socio Economic Research on Fusion) started in 2004.

TIMES generates economic models, technology-rich tools intended for the investigation of the local, national or multi-regional energy system evolution over a long term time horizon.

Far from being perfect forecasts, each scenario generated by these models is rather a picture of a possible future derived from a set of coherent hypotheses on the trajectories of the main socio-economic drivers of an energy system (e.g population, GDP, ...), and a set of constraints, such as an upper bound on GHGs emissions or upper/lower bound of installed capacity of a specific technology. Thus a scenario reflects the model's choices on which generation technologies are needed to meet the energy demand at minimum global cost while meeting environmental objectives and other constraints. The best option is derived by solving a system of equations which is the mathematical representation of the energy system. This is internally built by TIMES according to the declared technology fleet available at the beginning of the time horizon, its likely evolution in the future, the demand for energy and the energy source availability. In order to develop a detailed system of equations, EFDA-TIMES needs a set of qualitative and quantitative data about the energy system. The list of energy carriers and technologies acting in each sector of the energy system (upstream, industry, residential-commercial-agriculture, transportation and electricity and heat production), belongs to the qualitative data set whereas technological and economic assumptions specific to each technology, region and year, and their corresponding environmental emissions to the quantitative ones.

All technologies are both producers and consumers of commodities (such as energy carriers, materials, energy services and emissions), so EFDA-TIMES actually builds and manages an energy market, where a perfect competition among commodities is provided unless market imperfections, namely taxes, subsidies and hurdle rates or minimum rates of return (ROR), are introduced by the user. The optimal solution of the system of equations is the energy system configuration over a certain time horizon which maximizes the net total economic surplus or, similarly, minimizes the net total system cost while satisfying a number of constraints. Thanks to the assumption of linearity of technologies output to input functions, the system of equations is linear too and the optimal solution, i.e. the market equilibrium, can be derived using the technique of Linear Programming.

The EFDA TIMES model is specifically oriented to explore the role of fusion technology in a future energy market and identify which parameters affect its market competitiveness. Fusion power plants are assumed to reach the market deployment only in 2050, so the model time horizon covers the time range from 2005 (the base year) to 2100.

The world is subdivided in 16 macro-areas each corresponding to a so called “region” in the model, equipped with more than one thousand technologies. The data about the regional energy demand at the base year are mainly taken from IEA database. Future demands of energy services in each sector are instead linked to driver projections via elasticities. The projections of GDP, GDP per capita and production by sector, namely the demand drivers, are estimated externally with results from studies by GEM-E3 (Capros P. *et al.*, 2013), a general economic model, according to the figures for population, household growth rates (data from United Nation and IPCC) and technological progress given in input. The elasticities of demands to drivers used to develop the demand scenarios, i.e. a set of demand curves, have to be provided by the user. As regards the energy production sector, it is composed of three sections: the primary production of raw fossil fuels, biomass and nuclear fuel; the secondary transformation where the primary energy forms are turned into fuels for the end-use sectors and for electricity and heat generation; and finally the production of electricity and heat which is technologically explicit. Zero-emission-technologies and carbon sinks are also included.

GDP and all costs and prices are expressed in constant US dollars (year 2000) and the overall annual discount rate is fixed at 5% although some sectors and regions rely on specific discount rates that reflect financial characteristics typical of those regions.

### 3. Electricity generation technologies in ETM

One of the main strengths of ETM is that it is a technology-rich model consisting of a huge techno-economic database with more than one thousand of energy technologies for all the demand (residential, commercial, transport, industry and agriculture) and supply (power and heat generation and upstream) sectors. The table shows the power generation technologies included in the model:

Biomass	Crop direct combustion, Crop gasification, Biogas from waste, Solid biomass direct combustion, Solid biomass gasification,
Coal	IGCC, FBC, PFBC, Pulverised coal
Natural gas	NGCC, Combustion turbine, Fuel cells, Steam turbine
Oil	Combined cycle, Internal combustion
Gas oil	Combined cycle, Steam turbine
CCS	NG, IGCC, Pulverised coal, Fuel cells SOFC
Hydropower	Dam, Run of river
Geothermal	Binary high, Binary, Flashed steam
Ocean	Tidal, Wave
Solar	PV centralised and decentralised, CSP solar tower, CSP parabolic troughs
Wind	Onshore, Offshore
Fission	Advanced nuclear fast reactor, and LWR, FR (burner), ABR and ADS reactors
Fusion	Advanced reactor, Basic reactor

**Table 1.** Electricity generation technologies included in ETM

A range of potential fusion power plants were characterised in the EFDA's Power Plant Conceptual Study (PPCS) in 2005 (Maisonnier D. *et al.*, 2005). It included an assessment of the economic performance of all the plant concepts studied. Since then, other studies were carried out such as the EU DEMO study that allowed a later update of the initial data and were published by Han W.E. and Ward D.J. from EURATOM/UKAEA Fusion Association (Han W.E. and Ward D.J., 2009). Data from this last update has been used to define two fusion power plants:

	Date	Specific capital (\$ <sub>2000</sub> /kW)	Efficiency (%)	FIXOM (M\$ <sub>2000</sub> /GWa)	VAROM (M\$ <sub>2000</sub> /PJ)
Basic plant	2050	3,940	42	65.8	2.16
	2060	2,950	42	65.8	1.64
Advanced plant	2070	2,820	60	65.3	2.14
	2080	2,170	60	65.3	1.64

**Table 2** Data for the fusion technologies

In this paper we will present a set of scenarios aimed at analysing the role of fusion in the future energy market

Due to their intermittent nature, storage is a key factor in the integration and deployment of renewable technologies in the global electricity market. Special attention was then paid to new concentrating solar power (CSP) technologies with different storage levels as they seem to be emerging technologies with big potential for development at medium and long term. Three CSP technologies have been introduced into the EFDA TIMES model (see Table 3):

- Central tower with 1 hour storage (CT1)
- Parabolic trough with 7.5 hours storage (PT1), and
- Central tower with 15 hours storage (CT2).

	CT1	PT1	CT2
STORAGE (hours)	1	7.5	15
LIFE (years)	25	40	40
START	2006	2008	2011
INV_COSTS_2010 (\$ <sub>2000</sub> /kW)	3098	6151	11023
INV_COSTS_2020 (\$ <sub>2000</sub> /kW)	1859	3998	6614
INV_COSTS_2030 (\$ <sub>2000</sub> /kW)	1487	3279	5291
FIXOM_2010 (\$ <sub>2000</sub> /kW)	82	120	216
FIXOM_2020 (\$ <sub>2000</sub> /kW)	49	78	129
FIXOM_2030 (\$ <sub>2000</sub> /kW)	40	64	103

**Table 3.** Data for the CSP technologies

The data have been gathered from real solar thermal power plants working in Spain in 2011 published by the Spanish Association of the solar thermal power industry, Protermosolar (Protermosolar, 2011); the National Renewable Energy Laboratory in USA (NREL, 2011); the Spanish renewable energy magazine (Energías Renovables, 2011);

Gemasolar power plant promoter, Torresol Energy<sup>1</sup>; and the International network Solarpaces<sup>2</sup>.

For the data projections to 2020 and 2030, the assumptions about the costs evolution follow the technology roadmap CSP report from IEA (IEA, 2010). Availability factor (AF) and efficiency projections to 2030 come from (Energías Renovables, 2011).

Some of the technical data that define one electricity technology are the availability factor (AF) and the resource potential. The regional share of renewables is greatly influenced by the energy source potential and the technology availability over the year. While the first bounds the capacity, the latter has an impact on the energy production. Therefore the technology portfolio differs among regions according to the specific regional features. The characterization of the CSP technologies with storage has involved a broad analysis of suitable deployment areas for such facilities in terms of solar resource and potential with the support of a Geographical Information System (GIS). This tool has also been used to disaggregate the AF by CSP technology, region and time period. CSP plants can only be built in areas with direct normal irradiance above 1800 kWh/m<sup>2</sup>. Besides this limitation, other areas were also excluded such as protected areas and areas with slope higher than 2.1%. Moreover, only areas classified as bare and sparsely vegetated according to Global Land Cover 2000 databases were considered to be suitable for the installation of CSP plants. Suitable areas in each region (km<sup>2</sup>) together with the maximum production of solar electricity in these areas (assuming 16% solar to electricity efficiency) gave the restrictions of maximum electricity that can be produced in each region. Those results were introduced into the model as user constraints setting upper bounds to CSP power production.

Finally, AF was estimated for each region, time slice and CSP technology. AF depends on the location of the plants as well as on the season of the year. First, AF was calculated for a CSP plant without storage, taking into account the suitable areas in each region already identified, the season and time slice. From the resulting AF, the AF for CSP with storage plants has been calculated adding an extra availability resulting from the storage hours.

With regard to wind power it is assumed that an intensive utilization corresponds to a 4 MW/km<sup>2</sup> average power density (Hoogwijk *et al.*, 2004). Based on land classifications outlined by the Global Land cover 2000 database, suitable areas for wind turbine installations have been identified for each region. Offshore regions have been identified for elevation levels down to -80 m and onshore regions for elevation levels up to 2000 m above sea level. Due to regional varying average wind speeds three different availability classes have been distinguished. Low availability is considered for regions with less than 800 full load hours, mean availability for regions with up to 3000 full load hours and high availability for regions beyond 3000 full load hours of conventional wind turbines. Results from this survey have been taken as user constraints in the model for wind power production.

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<sup>1</sup> <http://www.torresolenergy.com/TORRESOL/home/en?swlang=en>

<sup>2</sup> <http://www.solarpaces.org/inicio.php>

#### 4. Scenario results

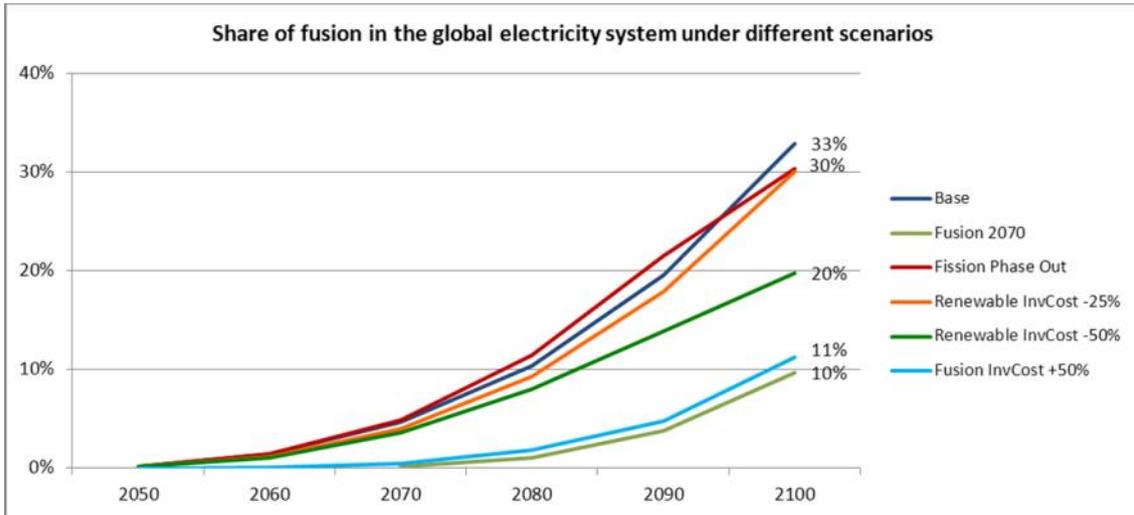
Fifteen different scenarios, described in the table below, have been built and explored.

Scenario	Descriptive name
Base	Environmental objective: 550ppm
Fusion2070	Base but fusion available from 2070
No fusion	Base + No fusion available
Fission Phase Out	Base + Fission nuclear plants phase out
Fusion InvCost	Base + Higher fusion investment costs, +50%
Low/High fusion O&M costs	Base + Lower/Higher fusion O&M costs, $\pm 20\%$
CSP InvCost	Base + Lower CSP investment costs, -50%; -25%; and -15%
Wind InvCost	Base + Lower wind investment costs, -50%; -25%; and -15%
Renewable InvCost	Base+ Lower CSP and wind investment costs, -25% and -50%

**Table 4.** Scenario definition

The “Base” scenario is taken as the Business as Usual scenario (BaU) because it considers the current environmental global objectives in the long term. Here the CO<sub>2</sub> concentration cannot exceed 550 ppm in 2100 (IPCC, 2000; 2007) and fusion is available from 2050 according to the so called “fast track” deployment. Nevertheless, a later commercial phase, i.e. from 2070 as envisaged in the recent Fusion Electricity Roadmap (EFDA, 2012) has also been modelled (scenario “Fusion2070”) so as to compare the fusion penetration in 2100 depending on the starting year. There are also two scenarios which explore various development paths of nuclear technologies. The first one, “No fusion”, is a scenario where fusion technologies are not available whereas the second, “Fission Phase Out”, is a scenario where there is no new fission power plant capacity installed. Finally, ten scenarios have been developed to explore the role of different variants of technology costs. Fusion costs variants include the scenarios: “Fusion InvCost” and “Low/High fusion O&M costs” where 50% higher investment costs and 20% lower and 20% higher operation and maintenance costs are taken for fusion technologies. The first scenario would simulate a great escalation of the cost of materials (similarly to what occurred in the period 2003 to 2008). The others would simulate the effects of different number of substitutions of replaceable components, which actually depend on their expected life, according to a Monte Carlo analysis. Renewable technology costs scenarios are “CSP InvCost” and “Wind InvCost” where 50%, 25%, and 15% lower costs are supposed for CSP and wind technologies individually. In “Renewable InvCost” both CSP and wind technologies costs are 25% and 50% reduced.

The penetration of fusion in the global electricity system has been analysed for the different scenarios and represented in Figure 1.



**Figure 1.** Fusion share in the global electricity system

The biggest penetration of fusion in the system takes place in the “Base scenario” where 33% of the electricity produced is generated by fusion power plants. If the fusion commercial plants enter the market in 2070 the technology share is 10% following the same trend in the production as in the Base scenario. It is worth noting that the total electricity production comprises not only the electricity generated in the electricity system but also the electricity produced in the industry sector such as autoproduction and combined heat and power (CHP). This may lead to higher electricity production than in other modelling exercises or scenarios which do not consider the electricity from industry.

The results show that the availability of technologies cheaper than fusion, such as renewables, does not prevent fusion penetration. Nevertheless, a reduction in the investments costs of both CSP and wind technologies of 25% would cut the share of fusion by 3%. If the reduction goes up to 50%, the share would be 13% lower.

The fusion energy costs have the biggest influence on fusion market chances. When these costs are 50% higher than those proposed in Table 2, “Fusion InvCost +50%” scenario, fusion penetration in the global system decreases dramatically. Therefore keeping fusion technologies competitive in terms of costs seems to be the main strategy for fusion to enter the electricity global system in the long term.

The electricity production from fusion technologies (see Figure 2) reaches the maximum in the “Fission Phase Out” scenario, with 9% more production than in the “Base” scenario. The lowest is in the “Fusion 2070” scenario where fusion technologies are not available until 2070.

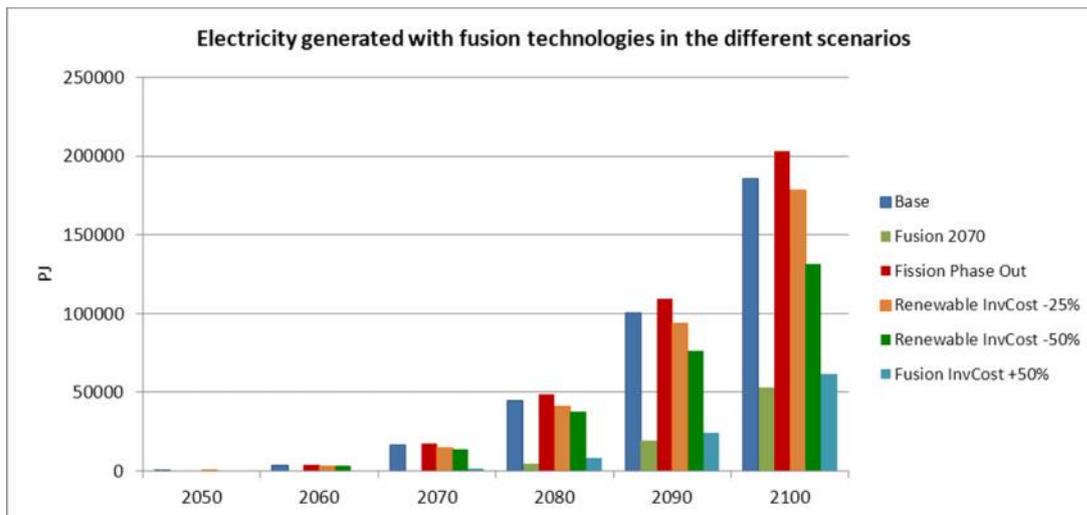


Figure 2. Electricity produced with fusion technologies

These scenario results are more extensively described in the next three sub-sections: fusion as a technology to meet the climate targets, the role of costs in fusion penetration and complementarity between fusion and fission technologies.

#### 4.1 Meeting the climate targets

The “Base” scenario considers a CO<sub>2</sub> concentration limit of 550ppm by 2100 according to the current climate global objectives (IPCC, 2007). Figure 3 shows the global electricity system composition for this scenario.

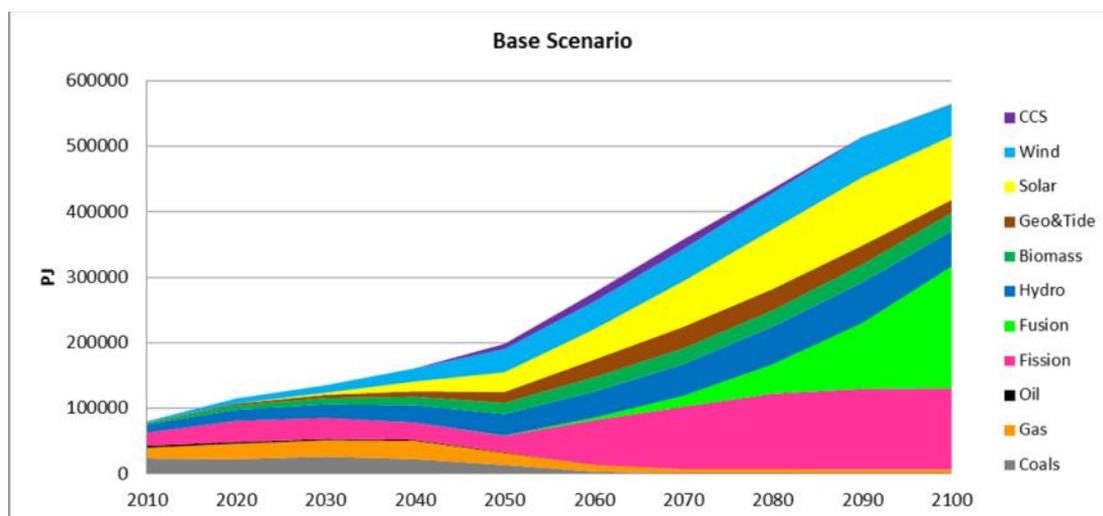


Figure 3. Base scenario

While fusion increases its share in the system, a decrease in fossil fuel use for power generation is experienced. Not only fusion technologies benefit from the climate restrictions but also other low carbon technologies, particularly nuclear fission and

renewables, especially the solar ones and the biomass in industry. From 2050 to 2100, fission power plants increase production by a factor of five while solar technologies treble. Regarding the fusion technologies, from 2050 to 2070 the electricity production comes from the basic plants only (see Table 2). Then, from 2070 the advanced plants became available contributing to 50% of the fusion electricity production in 2100.

The global electricity generation system in 2100 under the 550ppm climate target would supply 44% of electricity with renewable, 33% with fusion, 22% with fission and 1% with gas technologies.

In a less optimistic scenario where availability of fusion basic plants is delayed to 2070 and fusion advanced to 2090, the gap from 2050 to 2070 covered with fusion in the “Base” scenario is now shared among renewables and fission thus reaching 55% renewable and 34% fission in 2100. In this case the advanced reactors give a smaller contribution in the system in 2100.

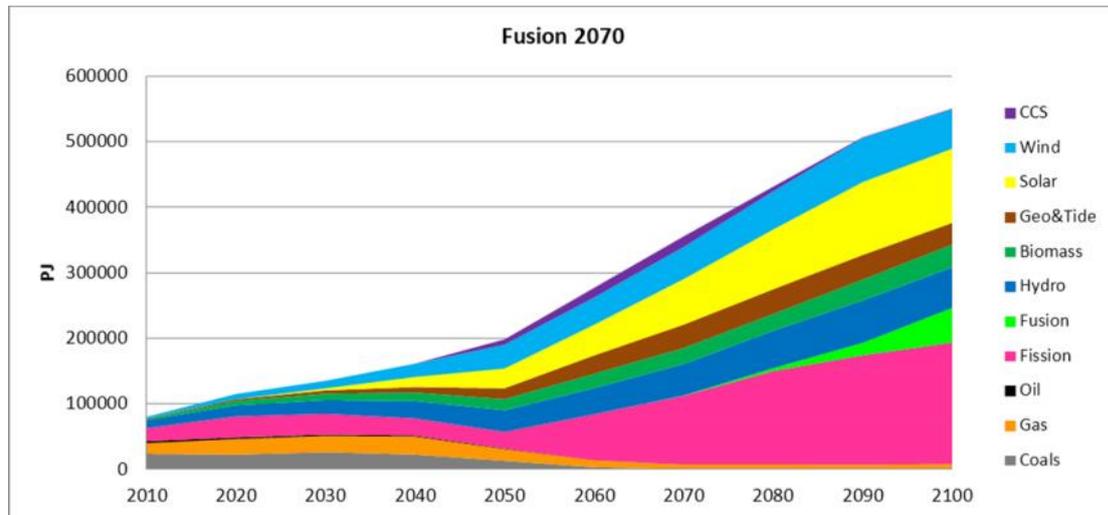


Figure 4. Fusion 2070 scenario

#### 4.2 Technology costs

In order to analyse the effect of the costs on the penetration of fusion technologies, a scenario with higher investment costs has been built as well as lower and higher operation and maintenance costs scenarios. With solar and wind being potential competitor technologies for fusion, other scenarios with lower costs for solar and wind technologies have also been created and analysed. Figure 5 shows the global electricity systems composition for the “Fusion InvCost +50%” scenario.

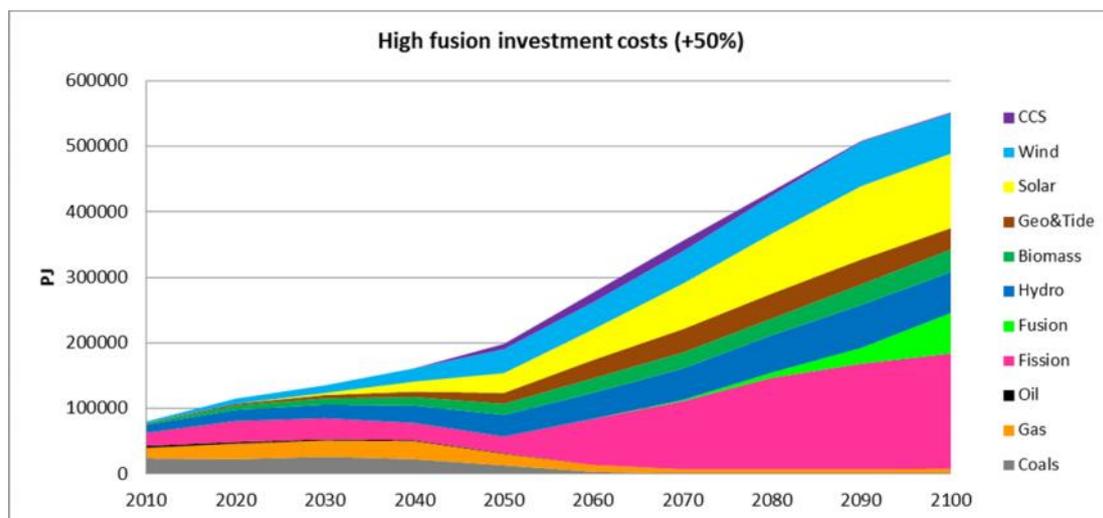


Figure 5. High fusion investment costs scenario

Fusion penetration into the global electricity system is strongly dependent on investment costs. When fusion costs are 50% higher, fusion power production decreases radically up to only a third of the production in the Base scenario in 2100. This situation would arise if, for example, a great escalation of the costs of materials occurs similar to that observed in the period 2003 to 2008. In this case, electricity from fusion is substituted by renewables and fission with productions, in 2100, close to 23% and 42% higher than in the Base scenario. This assumes that these technologies are unaffected by price escalations.

Regarding the effect of variations in the operation and maintenance costs for fusion technologies, two scenarios have been built where those costs grow and go down 20% with respect to the Base case. The results for those scenarios are shown in Figure 6.

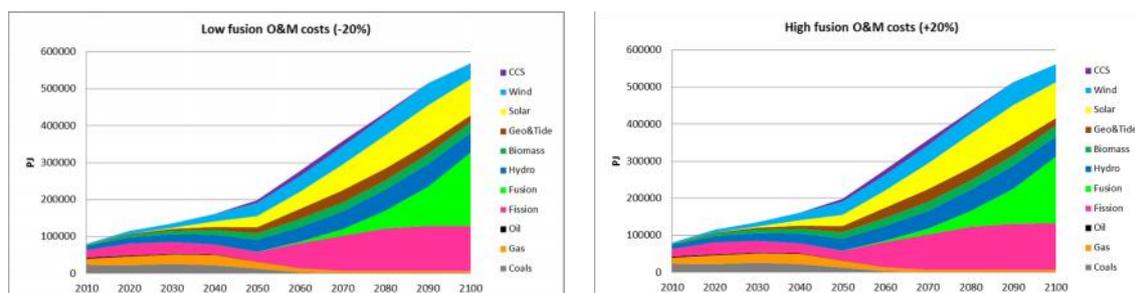
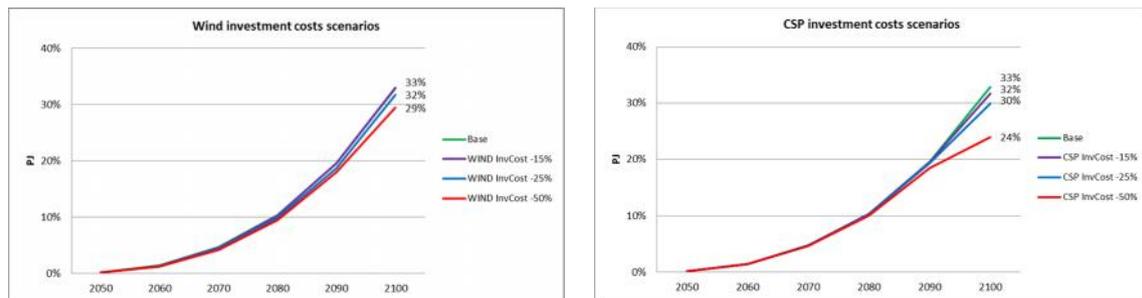


Figure 6. Operation and maintenance costs for fusion technologies scenarios

When the operation and maintenance costs decrease by 20%, the share of fusion technologies in 2100 increases by 2% with respect to the Base scenario. Conversely, when those costs increase by 20%, the share of fusion technologies in 2100 is reduced by 1%. In terms of production, when the operation and maintenance costs decrease by 20%, the production in 2100 is 7% higher than in the Base scenario while when the costs grow, the production in 2100 is 4% lower. The effect of reductions in the costs is bigger than the

effect of increments. According to the model results, fusion technologies penetration is more sensitive to a lowering of operation and maintenance costs than to a rise.

Investment costs for CSP and wind technologies scenarios have been built to look at the response of the system when CSP and wind costs are 50%, 25% and 15% lower than in the Base scenario. Results are shown in Figure 7.



**Figure 7.** Fusion share in low renewable costs scenarios

When wind technology costs are lower than in the “Base” scenario, the share of fusion in the electricity system slightly drops. For a cost reduction of 15%, the share is the same than in the Base case and higher reductions such as 50% result in lower shares but only 4% below the share in the Base case.

Regarding CSP technologies, the share of fusion also decreases with the CSP technologies costs but to a higher extent than in the previous scenarios of wind technology costs reductions. For 15% and 25% CSP technologies cost reductions, the share of fusion in electricity generation falls to 1% and 3% as compared to the Base scenario. But when the reduction of the costs is higher, 50%, it drops until reaching only 24%. CSP technologies, provided their costs are reduced in a sufficient level, are much more serious competitors than wind technologies.

The CSP technologies entering into the system are those with the highest availability factor i.e. those with the higher number of storage hours. The storage can make possible that this technology becomes a base load technology capable of substituting other base load technologies such as fusion or fission in those areas where the conditions are favourable. This is not the case for wind technologies with much more reduced availability factors.

Thus, an increased competition between fusion and CSP and wind technologies can appear when the costs of the CSP and wind technologies go down below 25% and 50% respectively. Whether or not these costs reductions are likely in the long term is still uncertain especially for wind technologies that are mature and commercial technologies today. For CSP technologies, although a cost reduction pathway has already been considered in the model, since it is still a technology under development, some further costs reductions could be expected.

### 4.3 Complementarity between fusion and fission technologies

So far, renewable technologies do not seem to be competitive with fusion technologies in the long term under climate restrictions provided that renewable technologies costs are not very much reduced. On the other hand, fission technologies have shown to be complementary to fusion technologies. In this last section two scenarios, a system without fusion and a system where fission phases out, are analysed. In the “No-fusion” scenario, fusion technologies are not available while in the “Fission-phase out” scenario, once the existing plants are decommissioned, new fission technologies are not installed in the global electricity system.

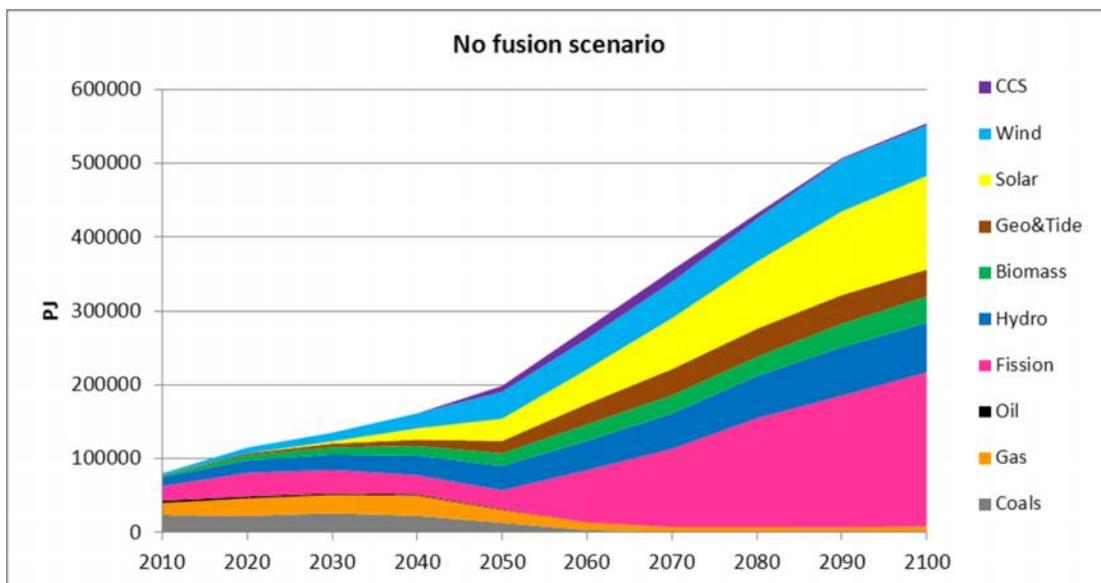


Figure 8. No fusion scenario

If fusion technologies are not available in the long term, most of the electricity production in 2100 comes from renewable (59% share) and fission (37% share) technologies. Within the renewable, electricity generated with solar and wind is 30% and 40% higher than in the Base scenario respectively. Electricity produced with fission technologies is 69% higher in the scenario with no fusion than in the Base.

In a scenario where new fission technologies are not installed, electricity by 2020 is mainly produced with fossil (54%), renewable (37%) and a small share of fission. From 2050, when fusion becomes available, generation with fossil fuels starts decreasing and is progressively substituted by fusion and CCS technologies, the latter playing an important role from 2070 to 2080 with shares around 18%. Fission power plants phase out after 2050. At the end of the period 68% of the electricity is produced by renewable and the rest is generated with fusion technologies. Fusion has completely substituted electricity from fossil fuels but does not affect renewable production which more than triple from 2050 to 2100.

The scenario with no fusion availability is the one with the highest production of electricity with CCS by 2100 even though it only means 1% of the total.

## **5. Conclusions**

The global energy model EFDA Times has been used to analyse the possible roles for fusion and renewable technologies in a low carbon global electricity system. This model covers the whole world divided into 16 regions and with a temporal horizon of 2100.

For the analysis fifteen different scenarios have been defined: the Base case scenario with a limit of 550ppm to GHG concentrations by 2100; the less optimistic Fusion 2070 scenario where fusion technologies are not available until 2070; the Fusion InvCost +50%; Fusion O&M cost  $\pm 20\%$ ; CSP InvCost -50%, -25% and -15%; Wind InvCost -50%, -25% and -15%; and Renewable InvCost -25% and -50% scenarios. To investigate further the interaction between fusion and fission, a No fusion and a Fission Phase Out scenario is included.

Looking at the results of the different scenarios, the main conclusion is that renewable technologies are fusion competitors in the long term only when the costs decrease more than 25% and 50% for solar and wind respectively. On the other hand, penetration of fusion in the electricity system does not affect the share or the production of renewable technologies. Regarding fission technologies, those have shown a close relation with the penetration of fusion into the electricity system in such a way that in a scenario where fission generation is excluded, all the electricity which would be generated with fission is produced with fusion, and in a scenario where fusion is not available, all the electricity generated with fusion in the base scenario is substituted by electricity produced by fission. It can be concluded that the nuclear technologies are complementary.

Assuming a large increase in fusion investment costs, as simulated by the Fus InvCost scenario, has a big impact on the penetration of the technology in the long term, reducing the share of fusion electricity production from 33% in the base case to 11%. Variations of operation and maintenance costs of fusion up to 20% up and down, that would arise from variations in the expected lifetime of replaceable components of the plant would not affect much (1-2%) the penetration of the technology.

The entry of fusion in the system contributes to the exit of fossil fuels and partially substitutes fission. Renewable technologies do not compete with fusion technologies in the long term unless the costs for these technologies are reduced substantially.

## 6. Acknowledgements

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