Energy Strategy Reviews 15 (2017) 1–8

Contents lists available at ScienceDirect

Energy Strategy Reviews

journal homepage: www.ees.elsevier.com/esr

Fusion power in a future low carbon global electricity system

H. Cabal [a,*], Y. Lechón [a], C. Bustreo [b], F. Gracceva [c], M. Biberacher [d], D. Ward [e], D. Dongiovanni [f], P.E. Grohnheit [g]

[a] Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Av Complutense, 40, 28040, Madrid, Spain
[b] Consorzio RFX, Associazione EURATOM-ENEA sulla Fusione, Corso Stati Uniti 4, 35127, Padova, Italy
[c] ENEA, Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Lungotevere Thaon di Revel, 76, 00196, Rome, Italy
[d] Research Studios Austria Forschungsgesellschaft mbH, Schillerstrasse 25, 5020, Salzburg, Austria
[e] CCFE, Culham Centre for Fusion Energy, Abingdon, Oxfordshire, OX14 3DB, United Kingdom
[f] ENEA, Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Via Enrico Fermi, 45, 00044, Frascati, Roma, Italy
[g] RISO-DTU, Frederiksborgvej 399, P.O. Box 49. DK-4000, Roskilde, Denmark

ARTICLE INFO

Article history:
Received 3 August 2016
Accepted 8 November 2016

Keywords:
Energy modelling
Global power system
Fusion technologies
Climate change

ABSTRACT

Fusion is one of the technologies that may contribute to a future, low carbon, global energy supply system. In this article we investigate the role that it may play under different scenarios. The global energy model ETM (originally EFDA TIMES Model) has been used to analyse the participation of fusion technologies in the global electricity system in the long term.

Results show that fusion technologies penetration is higher in scenarios with stricter CO_2 emissions reduction targets. In addition, investment costs and discount rates of fusion technologies are key factors for fusion implementation. Finally, the main competitors for fusion in future are Carbon Capture and Storage and fission technologies.

1. Introduction

EUROfusion promotes 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 and to help guide the R&D programme. Nuclear fusion would act in a context of an increasing energy demand due to the GDP growth in developing economies, population growth and the change in society's 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 ongoing. While ITER is being built, the conceptual 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 medium to 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 concentrates on the contribution of fusion power to a future low carbon global electricity system.

Abbreviations: ITER, International Thermonuclear Experimental Reactor; DEMO, Demonstration power plant; TIMES, The Integrated MARKAL-EFOM System; ETM, EFDA TIMES Model; SERF, Socio Economic Research on Fusion; PPCS, Power Plant Conceptual Study; DR, discount rate; CT, central tower; PT, parabolic trough.

* Corresponding author.
E-mail addresses: helena.cabal@ciemat.es (H. Cabal), yolanda.lechon@ciemat.es (Y. Lechón), chiara.bustreo@igi.cnr.it (C. Bustreo), francesco.gracceva@enea.it (F. Gracceva), markus.biberacher@researchstudio.at (M. Biberacher), david.ward@ukaea.uk (D. Ward), danilo.dongiovanni@enea.it (D. Dongiovanni), pogr@dtu.dk (P.E. Grohnheit).

http://dx.doi.org/10.1016/j.esr.2016.11.002
2211-467X/

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 and has continued to reflect ongoing changes in energy markets and in fusion R&D.

TIMES generates economic models, technology-rich tools intended for the investigation of the local, national or multi-regional energy system evolvement 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 global energy market and identify which parameters affect its market competitiveness. Fusion power plants are assumed to reach the market deployment in 2050, so the model time horizon covers the time range from 2005 (the base year) to 2100.

The world is subdivided in 17 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 the IEA database [1]. 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 [2]. GEM-E3 is 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 2005) 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 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. Table 1 shows the power generation technologies included in the model:

3.1. Nuclear technologies

A range of potential fusion power plants were characterised in the EFDA's Power Plant Conceptual Study (PPCS) in 2005 [3]. 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 [4]. Data from this last update have been used to define two fusion power plants but capital costs have been increased 50% to incorporate considerable raises in material prices in the last decade:

One of the last improvements in ETM has been the definition and implementation of the nuclear fission fuel cycle including the reprocessing of the fuel and waste management. Also Uranium and Plutonium from the decommissioning of nuclear weapons are considered as fuel sources.

3.2. Renewables

Due to their intermittent nature, energy storage, both on a daily and seasonal time scale, 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 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 h storage (CT1)
- Parabolic trough with 7.5 h storage (PT1), and
- Central tower with 15 h storage (CT2).

Data has been gathered from real solar thermal power plants working in Spain in 2016 published by the Spanish Association of the solar thermal power industry, Protermosolar [5]; the National Renewable Energy Laboratory in USA [6]; the Spanish renewable energy magazine [7]; Gemasolar power plant promoter, Torresol Energy [8]; and the International network Solarpaces [9].

For the data projections to 2020 and 2030, the assumptions about the costs evolution follow the technology roadmap CSP report from IEA [10]. Availability factor and efficiency projections to 2030 come from Ref. [7].

Some of the technical data that define one electricity technology

Table 1
Electricity generation technologies included in ETM.

Group	Technologies
Biomass	Crop direct combustion, Crop gasification, Biogas from waste, Solid biomass direct combustion, Solid biomass gasification,
Coal	Integrated gas combined cycle (IGCC), Fluidised bed combustion (FBC), Pulverised fluidised bed combustion (PFBC), Pulverised coal
Natural gas	Natural gas combined cycle (NGCC), Combustion turbine, Fuel cells, Steam turbine
Oil	Combined cycle, Internal combustion
Gas oil	Combined cycle, Steam turbine
CCS	Natural gas, Integrated gas combined cycle, Pulverised coal, Solid oxide fuel cell (SOFC)
Hydropower	Dam, Run of river
Geothermal	Binary high, Binary, Flashed steam
Ocean	Tidal, Wave
Solar	Photovoltaic centralised and decentralised, Concentrated solar power (CSP) solar tower and parabolic troughs
Wind	Onshore, Offshore
Fission	Light-water reactor, Fast reactor, Advanced burner reactor and Accelerator-driven system reactors
Fusion	Advanced reactor, Basic reactor

Table 2
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 3
Data for the CSP technologies.

	CT1	PT1	CT2
STORAGE (hours)	1	7.5	15
LIFE (years)	25	40	40
START	2006	2008	2011
INV_COSTS_2010 ($\$_{2005}$/kW)	3098	6151	11023
INV_COSTS_2020 ($\$_{2005}$/kW)	1859	3998	6614
INV_COSTS_2030 ($\$_{2005}$/kW)	1487	3279	5291
FIXOM_2010 ($\$_{2005}$/kW)	82	120	216
FIXOM_2020 ($\$_{2005}$/kW)	49	78	129
FIXOM_2030 ($\$_{2005}$/kW)	40	64	103

are the availability factor 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 Availability Factor (AF) by CSP technology, region and time period. CSP plants can only be built in areas with direct normal irradiance above 1800 kWh/m^2. 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 [11] were considered to be suitable for the installation of CSP plants. Suitable areas in each region (km^2) 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^2 average power density [12]. 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.

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

4. Scenario definition

Prior to scenario building, three different storylines describing a future world have been formulated (see Table 4) following the methodology from Ghanadan R. and Koomey J.G. [13]. First, a research question was posed, in this case *What can be the role of fusion technologies in the future global energy system?*, then several important forces in the environment affecting this future role of fusion were identified and, in a last step, those forces were weighted based on their uncertainty and importance. The main five resulting critical forces were public acceptance, GDP, technology, climate change and energy costs.

Those storylines have been afterwards quantified into scenarios using different parameters. To introduce the environmental responsibility, elasticity of energy service demands to their drivers has been used in a way that the stronger the responsibility, the lower the elasticity. The "Base" elasticities are results of the GEM-E3 model, and then strong and weak environmental responsibilities have been modelled using elasticities 30% lower and higher than Base respectively. The term view used by operators or investors has been introduced by means of the technology specific hurdle rate, the longer the term view, the lower the rate. Finally, for the CO_2 emissions targets, two Representative Concentration Pathways (RCP) have been followed, RCP6 and RCP4.5, described in Table 5.

Those pathways are translated into CO_2 emissions limits of 48.2 GtCO2 in 2050 and 50.4 GtCO2 in 2100 for RCP6, and 36 GtCO2 in 2050 and 14.4 GtCO2 in 2100 for RCP4.5.

Besides studying the effects of different attitudes towards the energy issue on the fusion technology deployment, sensitivity analyses of nuclear fusion penetration on specific financial and technical parameters have been carried out taking Paternalism as base case. Specifically, the dependence of the fusion electricity share on the hurdle rates has been investigated in the scenarios LDR (low hurdle rates) and HDR (high hurdle rates). The hurdle rates of the electricity generating technologies are increased by 50% in HDR scenario with respect to the base case, while similarly decreased in the LDR scenario. Moreover, the weight of fusion capital cost on the electricity generation mix has been assessed through the scenarios +30%InvCosts and −30%InvCosts where the overnight costs of the fusion technology are increased and decreased by 30% respectively. These scenarios reflect the high uncertainty on the economics of fusion. Since the capital cost of a fusion power plant is obviously uncertain at this stage, sensitivity analyses can contribute to the identification of the cost ranges that would turn into a relevant electricity generation in a future energy system. Finally also the worst case, i.e. the fusion absence in a future energy mix presumably due to unsolved technical and physical issues is considered in the No availability scenario. This option is useful to identify the main fusion competitors.

Table 6 shows all the scenarios analysed.

5. Results and discussion

In all the scenarios analysed fusion is made available from 2050 according to the so called “fast track” deployment. Nevertheless, the global energy system evolution resulting from the total system cost minimisation does not include fusion before 2070 in any case due to the high investment cost in the first years.

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

The highest penetration of fusion in the three storylines takes place in Harmony where 14% of the electricity produced in 2100 is generated by fusion power plants, followed by Paternalism with 13% (both are superposed in the figure) and Fragmentation with 10%. Harmony and Paternalism have in common the very strict CO_2 emissions limits in contrast with Fragmentation. Thus fusion electricity gains a larger share being fusion a carbon-free technology.

Regarding the results of the different sensitivity analyses, the most favourable scenario for fusion is the one with the lower investment costs which results in 42% share of fusion technologies in the total global system. On the other hand, the less favourable scenario for fusion is the one with the higher investment costs, in fact, an increase in the costs above 30% will result in fusion technologies not entering the system. Also, lower discount rates for fusion technologies lead to a higher participation of fusion technologies while higher discount rates have the opposite effect.

These scenario results are more extensively described in the next four sub-sections: fusion as a technology to meet the climate targets, the effect of technology discount rate in the future electricity system, the role of investment costs in fusion penetration, and the composition of the electricity system in the case that fusion is not available.

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 self-production 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.

5.1. Meeting the climate targets

Harmony and Paternalism scenarios are the ones which consider the strictest CO_2 concentration limit, 650 ppm by 2100. Results on the global electricity system evolution are shown in Fig. 2.

In Paternalism, electricity production with conventional fossil fuel technologies continues growing until 2040 when Carbon Capture and Storage (CCS) becomes available. From then on the fossil generation is largely based on coal power plant equipped with CCS (9% in 2050) while there is not contribution from gas fuelled power plants with CCS due to the high cost of natural gas. Wind and solar PV technologies experience a great increase and cover nearly 1/6 of the electricity generation in 2050. But after 2070, when fusion technologies enter the system, CCS starts being substituted by nuclear technologies while wind and solar technologies remain the same. The global electricity generation system in 2100 in Paternalism would supply 64% of electricity with renewable, 13% with fusion, 8% with fission (advanced LWR), and 15% with fossil fuel technologies, corresponding 13% to CCS. In this scenario, the average growth rate for fusion technologies is 12%/year.

Similar to Paternalism but with less electricity production due to the assumption of a strong environmental responsibility, Harmony presents also a high participation of fusion and renewable technologies in 2100, 14% and 75% respectively, and mainly differs from Paternalism in a lower share of fossil fuel technologies, 3% and 2% without and with CCS respectively. In Harmony, the average growth rate for fusion technologies is also 12%/year.

Finally in Fragmentation, where environmental responsibility is

Table 4
Storylines.

Storyline	Description
Harmony	- Strong environmental responsibility - Operators take a long-term view when deciding their investments - Very stringent global carbon emissions target and all regions cooperate
Paternalism	- Mixed environmental responsibility - Operators take a medium-term view when deciding their investments - Very stringent global carbon emissions target and all regions cooperate
Fragmentation	- Weak environmental responsibility - Operators take a short-term view when deciding their investments - Flexible global carbon emissions target and not all regions cooperate

Table 5
Representative Concentration Pathways considered in the scenarios.

	Radiative forcing	Concentration
RCP4.5	~4.5 W/m^2 at stabilization after 2100	650 ppm CO_{2eq} at stabilization after 2100
RCP6	~6 W/m^2 at stabilization after 2100	850 ppm CO_{2eq} at stabilization after 2100

Source: [14].

Table 6
Scenario matrix.

Scenario	Elasticity	Hurdle rate	CO2 limit	Fusion invest costs	Fusion availability
Harmony	−30% Base	−50% Base	RCP 4.5	Base (Table 2)	Yes
Paternalism	Base	Base	RCP 4.5	Base (Table 2)	Yes
LDR	Base	−50% Base	RCP 4.5	Base (Table 2)	Yes
HDR	Base	+50% Base	RCP 4.5	Base (Table 2)	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 (Table 2)	Yes

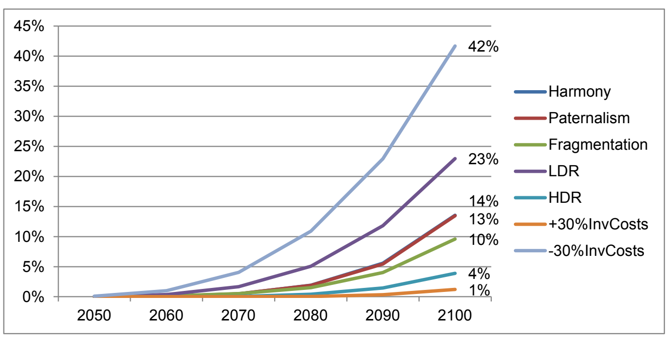

Fig. 1. Fusion share in the global electricity system.

weak and global carbon emissions target is more flexible, electricity production is higher and there is an important participation of coal and gas technologies, 23% with CCS and 17% without CCS. In Fragmentation, renewable technologies are responsible of 48% of the total production in 2100, the lowest share in the three scenarios, as nuclear technologies where fusion ones produce 10% of the total and fission ones 3%. The average growth rate for fusion technologies in this scenario is also the lowest with 0.9%/year.

Fusion technologies present the highest participation in the global electricity system in a world with a strong environmental responsibility and a stringent global carbon emissions target. In this world, renewable technologies produce more than two thirds of the electricity and the system is almost decarbonised with only a share of 1% and 3% of fossil fuel technologies without CCS in Paternalism and Harmonisation respectively.

5.2. Discount rates

Sensitivity analysis on technology discount rates for all the technologies has been performed using Paternalism as Reference

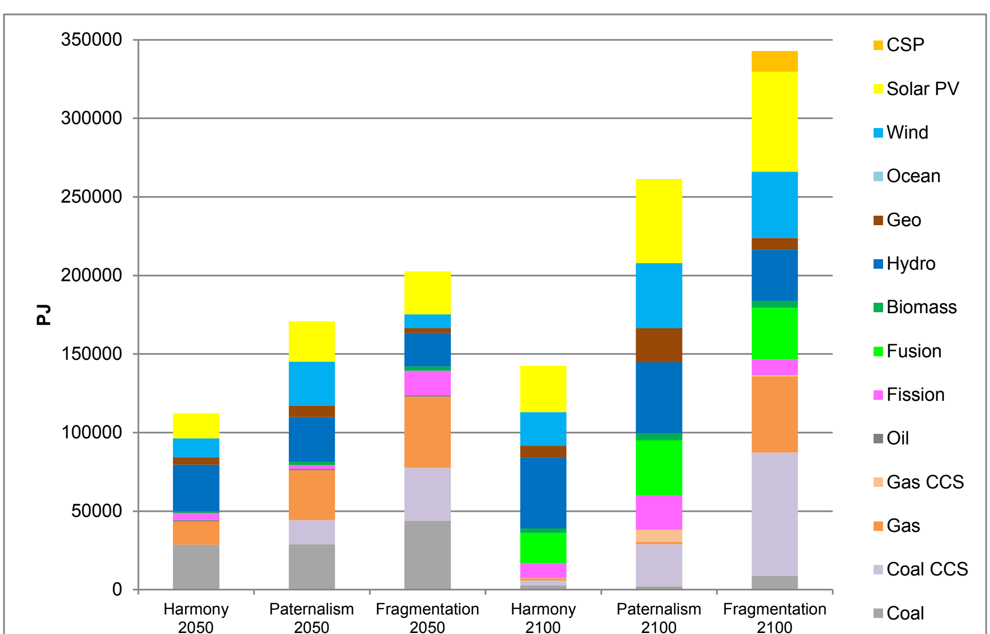

Fig. 2. Electricity production in 2050 and 2100 for the three scenarios.

case. In this case, the rate for fusion technologies is 10%. When the rate is lower, 5%, the technology share is 23% against the 4% share when the rate is higher, 20% (see Fig. 2). The lower the discount rate, the higher the penetration of fusion technologies in the system is. Fusion is in fact a capital-intensive technology and the capital cost accounts for pprox. 70% of the cost of electricity (see Maisonnier D. et al., 2005). Therefore, lower discount rates turns into lower cost of capitals and cheaper electricity.

The differences in the electricity system composition in each scenario are shown in Fig. 3. In positive, there are represented the technologies with higher production in the high discount rate scenario (HDR) while in negative there are the technologies with higher production in the low discount rate one (LDR).

A higher discount rate favours the penetration and development of CCS technologies with gas and coal from 2040, in fact, in 2100 the share of CCS technologies means 39% of the total. This is the main difference regarding low discount rates where CCS technologies in 2100 produce only 3% of the total electricity and nuclear and renewable technologies, mainly solar PV, hydropower and wind power, have a bigger share, especially the first ones from 2070 to 2100. Both electricity systems are carbon free but in HDR the system still relies significantly on fossil fuels while in LDR this dependence is mainly on nuclear fuels.

5.3. Technology costs

Also sensitivity analysis on fusion technology investment costs has been carried out using Paternalism scenario as Reference case and results show that costs have the biggest influence on fusion market chances. When these costs are 30% higher than those proposed in Table 2, fusion penetration in the global system decreases dramatically until it reaches 1% in 2100. That indicates that costs more than 30% higher lead to the no participation of fusion technologies in the electricity market. In this case, electricity from fusion is substituted by CCS and fission technologies with productions, in 2100, close to 38% and 37% higher than in the Paternalism scenario.

On the contrary, when costs are 30% lower, the share of fusion technologies reaches 42% in 2100, the maximum in all the scenarios analysed. Here fusion power production increases radically up to three times the production in 2100 in the Paternalism scenario.

Fig. 4 shows the difference in electricity production by technology between the low costs and the high costs scenarios. In positive, there are represented the technologies with higher production in the low cost scenario (−30%InvCosts) while in negative there are the technologies with higher production in the high cost one (+30%InvCosts).

5.4. No fusion availability

In this last section a system without fusion is analysed in order identify technologies which may be potential competitors. Paternalism scenario has been taken with the constraint of no fusion technologies availability. Resulting electricity system composition is shown in Fig. 5. In positive, there are represented the technologies with higher production when fusion is not available (No

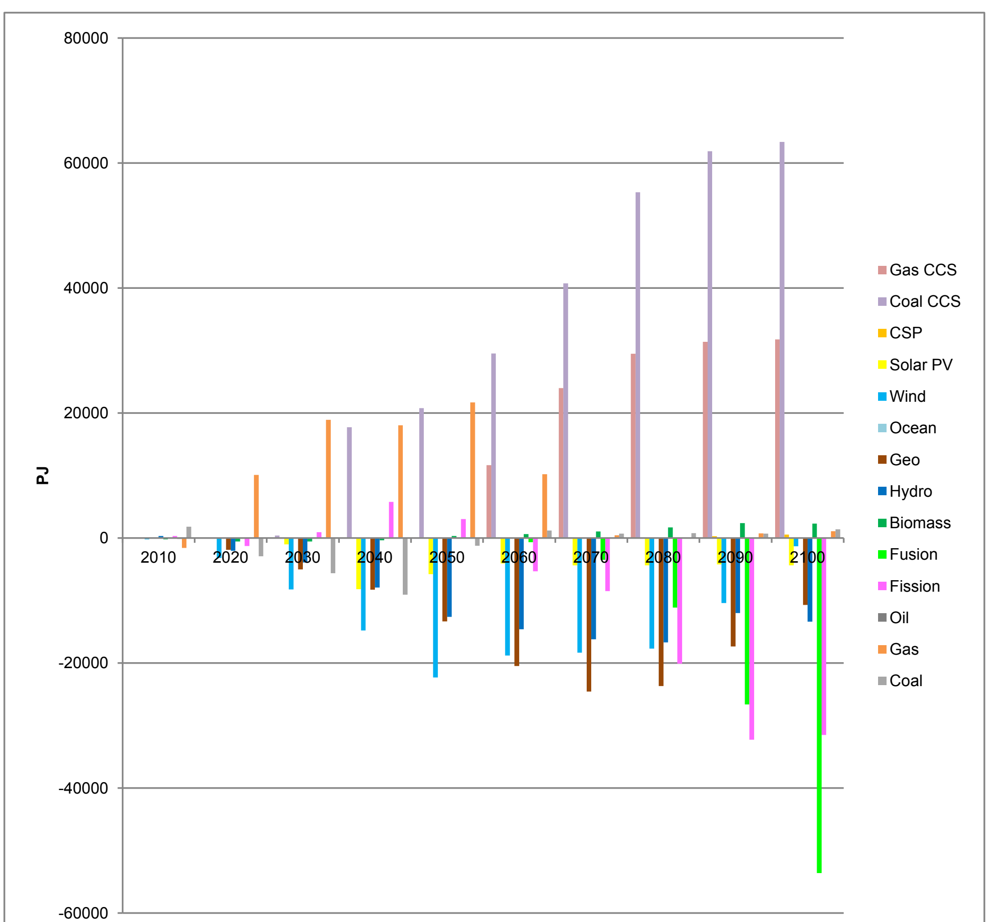

Fig. 3. High discount rate versus low discount rate scenarios.

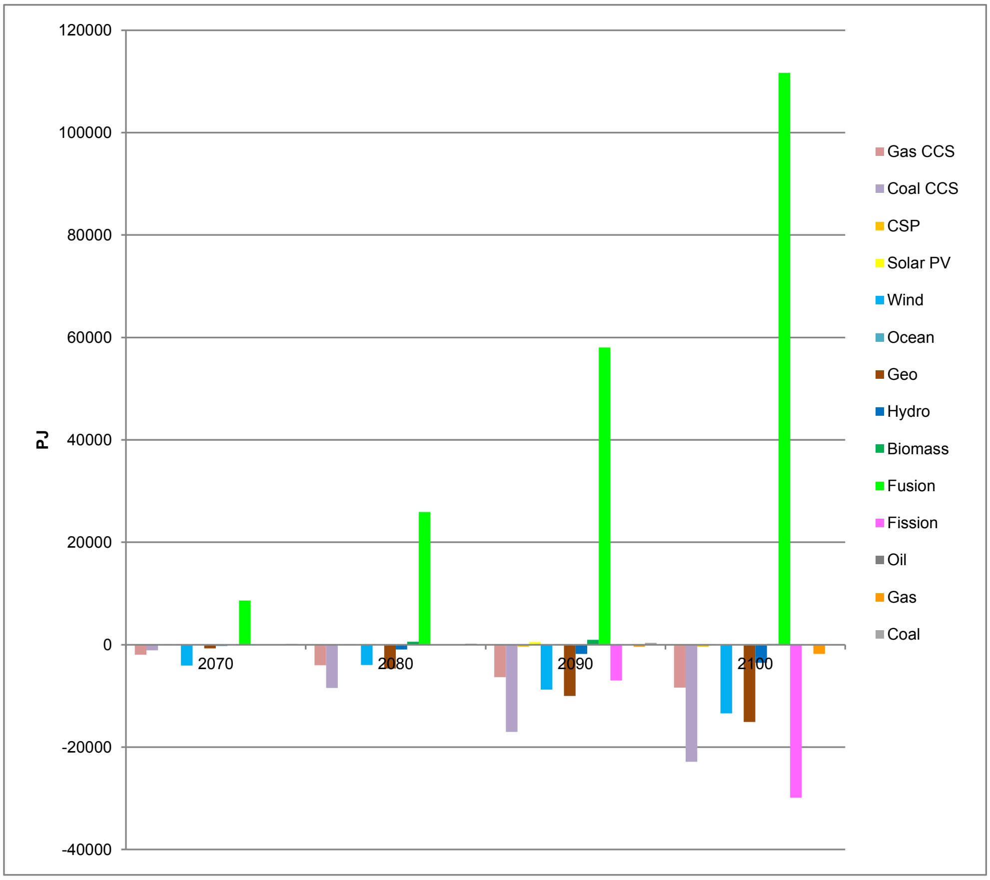

Fig. 4. Low costs versus high costs scenarios.

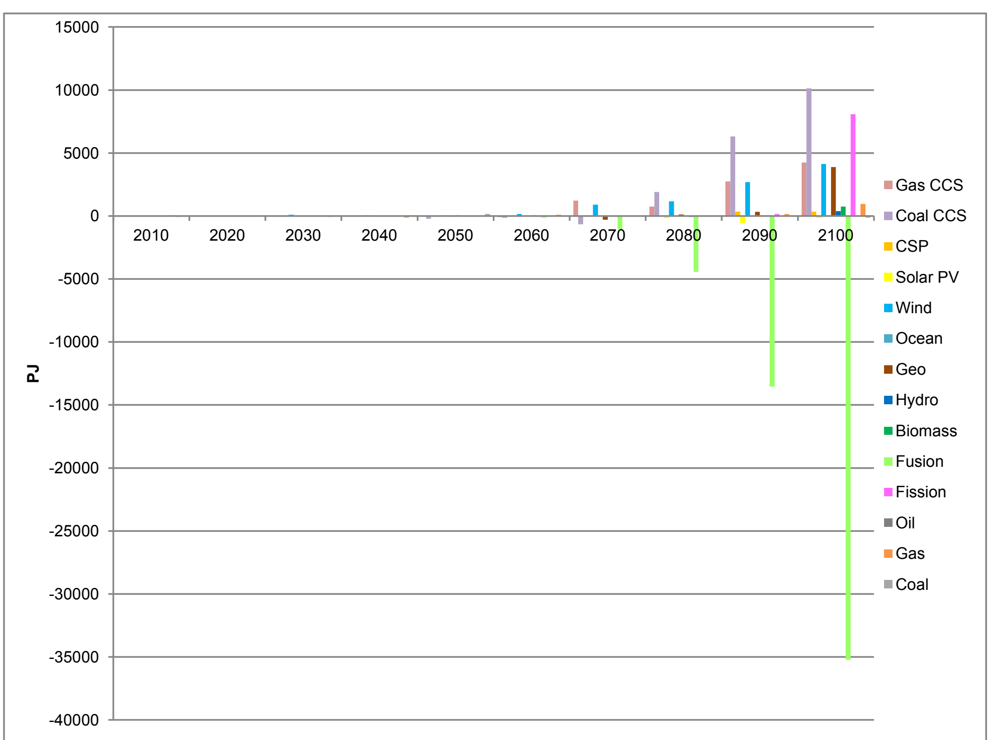

Fig. 5. No fusion scenario.

Availability).

In this case, most of the electricity production in 2100 comes from renewable (68% share) and CCS (19% share) technologies. Fusion technologies are mainly replaced by CCS and fission technologies whose production grows 42% and 37% respectively regarding the Paternalism scenario.

6. Conclusions

The global energy model ETM (EFDA TIMES Model) has been used to analyse the possible role for fusion technologies in a future global electricity system. This model covers the whole world divided into 17 regions and with a temporal horizon of 2100.

For the analysis eight different scenarios have been defined: three scenarios with different assumptions on environmental responsibility, CO2 emissions limits and term view for operator to make their investments; two scenarios with different assumptions on technology discount rates; two scenarios with different assumptions on fusion technology investment costs; and one scenario with no fusion availability.

Looking at the results of the different scenarios, the main conclusion is that in a world with a strong environmental responsibility and a stringent global carbon emissions target, fusion technologies present the highest participation in the global electricity system and contribute, together with renewable technologies, and in a minor proportion, CCS technologies to achieve an almost fully decarbonised global electricity system.

Discount rate is a key factor in the development and implementation of technologies and in the case of fusion power plants the results show that the lower the rate, the higher the penetration in the system is in contrast to CCS technologies favoured by high discount rates.

Assuming a large increase in fusion investment costs has a big impact on the penetration of the technology in the long term, reducing the share of fusion electricity production from 13% in the reference case to 1%. 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.

In case that fusion was not available in future, the main competitors are CCS and fission technologies which increase their production by 42% and 37% respectively.

Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] International Energy Agency, World Energy Statistics and Balances, OECD/IEA, Paris, 2010.
[2] P. Capros, D. Van Regemorter, L. Paroussos, P. Karkatsoulis, GEM-E3 Model Documentation, JRC Technical Reports, 2013.
[3] D. Maisonnier, I. Cook, P. Sardain, L. Boccaccini, E. Bogusch, K. Broden, L. Di Pace, R. Forrest, L. Giancarli, S. Hermsmeyer, C. Nardi, P. Norajitra, A. Pizzuto, N. Taylor, D. Ward, The European power plant conceptual study, Fusion Eng. Des. 75–79 (2005) 1173–1179.
[4] W.E. Han, D.J. Ward, Revised assessments of the economics of fusion power, Fusion Eng. Des. 84 (2009) 895–898.
[5] Protermosolar, Mapa de proyectos en España. http://www.protermosolar.com/proyectos-termosolares/mapa-de-proyectos-en-espana/, 2016 (Accessed 11 March 2016).
[6] National Renewable Energy Laboratory, Concentrating Solar Power Projects in Spain. http://www.nrel.gov/csp/solarpaces/by_country_detail.cfm/country=ES, 2016 (Accessed 23 March 2016).
[7] Energías Renovables. Solar termoeléctrica. España, protagonista mundial. Energías Renovables, nº 102, Julio-Agosto, 2011.
[8] Torresol Energy, Homepage. http://www.torresolenergy.com/TORRESOL/home/en?swlang=en, 2016 (Accessed 2 August 2016).
[9] Solar Paces Organisation, Homepage. http://www.solarpaces.org/inicio.php, 2016 (Accessed 2 August 2016).
[10] International Energy Agency, Technology Roadmap. Concentrating Solar Power, OECD/IEA, Paris, 2010.
[11] European Environment Agency, Global Land Cover 2000 – Europe, 2006. Available at: http://www.eea.europa.eu/data-and-maps/data/global-land-cover-2000-europe.
[12] M. Hoogwijk, B. de Vries, W. Turkenburg, Assessment of the global and regional geographical, technical and economic potential of onshore wind energy, Energy Econ. 26 (2010) 889–919.
[13] R. Ghanadan, J.G. Koomey, Using energy scenarios to explore alternative energy pathways in California, Energy Policy 33 (2005) 1117–1142.
[14] Richard Moss, Mustafa Babiker, Sander Brinkman, Eduardo Calvo, Tim Carter, Jae Edmonds, Ismail Elgizouli, Seita Emori, Lin Erda, Kathy Hibbard, Roger Jones, Mikiko Kainuma, Jessica Kelleher, Jean Francois Lamarque, Martin Manning, Ben Matthews, Jerry Meehl, Leo Meyer, John Mitchell, Nebojsa Nakicenovic, Brian O'Neill, Ramon Pichs, Keywan Riahi, Steven Rose, Paul Runci, Ron Stouffer, Detlef van Vuuren, John Weyant, Tom Wilbanks, Jean Pascal van Ypersele, Monika Zurek, Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies, Technical Summary, Intergovernmental Panel on Climate Change, Geneva, 2008, p. 25.