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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, 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.

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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 multiregional 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 socioeconomic 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