The Potential Role for Fusion Power in Future Energy Markets

P. Muehlich[a1], M. Biberacher[b], H. Cabal Cuesta[c], U. Ciorba[d], C. Eherer[e], F. Gracceva[d], P. E. Gronheit[f], T. Hamacher[a,g], W. Han[h], Y. Lechon[c], A. Pina[i], D. Ward[h]

[a] *Max-Planck-Institut für Plasmaphysik, Garching, Germany*
[b] *iSPACE, Salzburg, Austria*
[c] *CIEMAT, Madrid, Spain*
[d] *ENEA, Rome, Italy*
[e] *EFDA CSU, Garching, Germany*
[f] *Risø DTU, Roskilde, Denmark*
[g] *Technische Universität München, München, Germany*
[h] *UKAEA, Oxfordshire, United Kingdom*
[i] *IST, Lisboa, Portugal*

Abstract. In order to explore the possible role of fusion power in future energy markets a global energy scenario model has been developed. This model covers the whole of the 21st century and includes fusion power plants as a possible energy option. Our model is driven by energy service demands in five different end use sectors. Due to substantial economic growth in emerging economies we find a four fold increase in global primary energy consumption and a seven fold increase in global electricity demand at the end of the model time horizon. We have developed a series of scenarios reflecting various assumptions on future policy and economic developments. Albeit fusion power is a cost intensive technology substantial market shares can be expected in a world earnestly striving for climate change mitigation. This, however, strongly depends on future developments and acceptability of nuclear fission technologies. Our model is presented and first results with a strong focus on the electricity sector are discussed. This work is being carried out within the framework of the European Fusion Development Agreement.

1 Introduction

With the construction of ITER fusion research efforts make a transition from laboratory to industrial scale. It is this transition in the fusion development program which has motivated this new assessment of the role for fusion in future energy markets. Although fusion is far from commercial use, refined ideas were developed on how fusion power plants might look like [1, 2]. Parts of the work presented here are based on the European PPCS study [1, 2, 3]. A comprehensive description of the EFDA TIMES energy system model and a more complete discussion of scenario results as presented here will be available soon [4].

Today, the views on the long term development of the global energy system converge at least to a certain degree among analysts. While carbon capture and storage provides a transition technology because of the finite storage capacities [5] and biomass is expected to play a major role rather in energy sectors other than the electricity sector (e. g. [6]), mainly four long term energy options remain: Nuclear fission using breeder reactors, nuclear fusion, geothermal energy and solar energy of various forms (e. g. wind power) [7]. While the ultimate answer to the energy challenge certainly has to be a mixture of these solutions [8, 9] it is the aim of the present study to assess the potential role of fusion power within the energy economy of the 21st century. See also [10, 11, 12, 13] for earlier studies.

[1] *Email address:* pascal.muehlich@ipp.mpg.de

2 Model

The EFDA TIMES energy model is a global long term partial equilibrium model of the entire energy system [4, 14]. It uses the integrated MARKAL-EFOM system (TIMES) provided by IEA-ETSAP [15, 16, 17]. The model dynamics is determined by a maximization of total economic surplus (which – if demands are not price elastic – is equivalent to a minimization of overall costs) which is realized by the TIMES model generator using linear programming techniques. The EFDA TIMES model is globally disaggregated into 15 world regions. It covers a time horizon from 2000 to 2100 distributed over 12 model periods of variable length. Similar global multi-regional MARKAL-TIMES models have been used for the preparation of other important long term energy technology evaluation studies [18, 19, 20].

The topology of the energy system is structured via 7 distinct energy sectors. Aside from the upstream and electricity sectors these comprise the five end-use sectors agriculture, industry and the commercial, residential and transport sectors. The model is driven by energy service demands in each of these sectors. The demands are computed from a coherent set of demand drivers obtained from a general equilibrium model[21]. This is done by choosing elasticities which describe the strength of the coupling between driver and demands:

$$\text{Demand} = \text{Driver}^{\text{Elasticity}}.$$

Within the present study the set of drivers and elasticities is not varied among different scenarios.

2.1 Scenario definition

Fusion power plants will not be available for commercial use before the mid of this century. Thus, a discussion of the performance of fusion power in future energy markets makes sense only within a long term picture. As it is not possible to obtain reliable predictions of such long term time horizons the future energy market must be investigated by means of so-called scenario studies. Here, a scenario comprises a set of coherent assumptions about the future trajectories of the main drivers of the system, the resource availability, technical parameters and policy measures, together forming a credible storyline. Results of an evaluation of our model without any climate constraints define the BAU scenario.

We study different CO_2 mitigation scenarios via a set of policy assumptions. Presently CO_2 constitutes the only greenhouse gas considered within the EFDA TIMES framework. Consequently, a scenario allowing for a total atmospheric CO_2 concentration of 550 ppm can be roughly compared to a 650 ppm CO_2 equivalent scenario as other climate relevant gases are not limited [22]. The CO_2 mitigation pathways used as input to the present scenario studies have been obtained in [23]. Total emissions in the considered policy scenarios CO2_650PPM and CO2_550PPM together with the amounts of CO_2 captured via CCS technologies are shown in Figure 1. Further scenarios addressing certain technology cost components and resource availabilities will be discussed subsequently.

2.2 Fusion parameters

As part of the PPCS (Power Plant Conceptual Study) in Europe, published in 2005 [1, 2], an assessment was made of the likely economic performance of the range of fusion power plant concepts studied. Recently new information from the EU DEMO study [24] has been used and reduced cost versions of the PPCS plant models or, alternatively, plants with less ambitious technical assumptions at constant cost could be obtained. Explicit paramter values are given in [3].

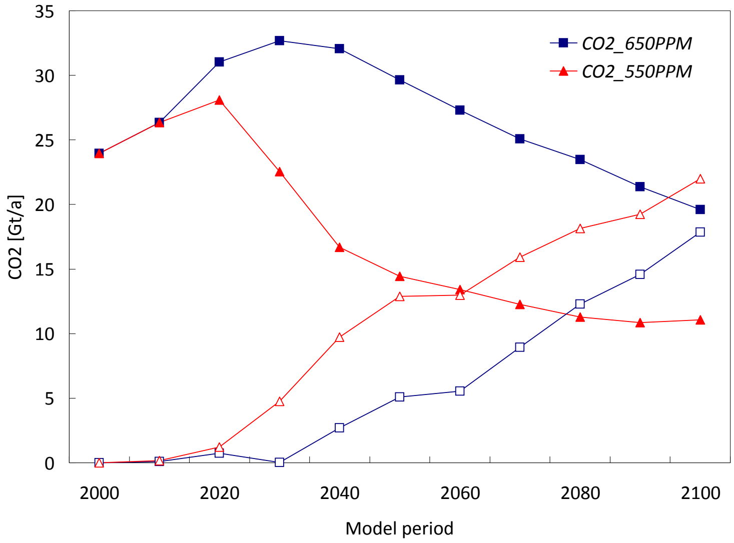

FIG. 1: Total global CO_2 emission pathways for two policy scenarios. In addition the annual amounts of CO_2 captured by CCS technologies (open symbols; employed technologies: afforestation, deep saline aquifers, and deep ocean storage) are shown. In the BAU *scenario (not shown in the figure) global emissions keep on growing up to a level of 90 Gt/a.*

Scenario		BAU	CO2_650PPM	CO2_550PPM
Energy intensity	2000	12.68		
[MJ/$\$_{2000}$]	2050	7.66	7.37	7.59
	2100	4.47	4.03	3.64
Carbon intensity	2000	67.90		
[kt/PJ]	2050	61.74	40.56	19.19
	2100	61.81	14.86	9.30
Electrification	2000	0.138		
	2050	0.239	0.247	0.304
	2100	0.253	0.312	0.371

TAB. 1: Global energy indicators for three policy scenarios. All quantities are calculated with respect to primary energy.

3 Results

Let us first discuss some general features of the studied scenarios. Table 1 shows a set of typical indicators of the global energy economy for all policy scenarios. In all cases a substantial decline of energy intensity is observed. This behavior is in agreement with most other energy scenario studies (e. g. [25]) and is a typical sign of growing welfare as with higher income levels more efficient conversion and end-use technologies become affordable. As expected, energy is used even more efficiently in the CO_2 restricted scenarios due to the additional impact of the environmental constraint. The size of this effect, however, is certainly limited due to the few options considered in the model to reduce the end energy demand. This will be improved in future model versions by including more groundbreaking energy efficiency measures.

Most pronounced, carbon intensity changes only marginally in the BAU scenario. In contrast, both CO_2 mitigation scenarios show a substantial decline of carbon intensities which is a sign of the turning away from the use of fossil energy carriers. Also electrification shows a pronounced difference between policy scenarios. While it roughly doubles in the base case, in the CO2_550PPM scenario almost a triplication can be observed. Consequently, we find in spite of the increase in energy intensity (and, thus, a decline in primary energy use) also an increase in total electricity need as the environmental constraint is tightened.

3.1 Electricity generation

Figures 2 through 4 show global electricity generation levels for the three policy scenarios. In 2100 all scenarios exhibit a strong increase of todays electricity generation levels (factor 7.6 in BAU, 8.4 in CO2_650PPM and 9.1 in CO2_550PPM). In the BAU scenario no policy constraints are applied. Thus, the results in this case are entirely driven by the TIMES rationale of minimizing overall costs. As a consequence, a strong revitalization of coal in the electricity sector can be observed. This is largely responsible for the huge increase of global carbon emissions (90 Gt/a in 2100, compare to Figure 1). At the same time the market share of nuclear fission grows strongly, however, without reaching the levels of coal. Interestingly the market share of nuclear fission only grows in the second half of the century. It is pushed into the market by the large demand growth in emerging economies. Also renewable energy and hydro power capacities are extended without playing a major role in the unconstrained scenario. Fusion power does not at all enter the market.

A completely different picture emerges if stringent greenhouse gas emission targets are applied, see Figures 3 and 4. In both cases an admixture of renewable energies (mainly hydro power and wind) and nuclear fusion come to dominate the electricity market in 2100. While nuclear fission starts to dominate the picture from 2040 onwards, fusion starts to take over from 2080. This, however, is the result of the Uranium resource constraint built in the model. Uranium resources are depleted in spite of the quite optimistic resource base assumed (equivalent to 17,500 EJ of thermal energy extracted with a conventional LWR). This issue will be discussed in more detail in a following section. In both CO_2 mitigation scenarios fusion power obtains large market shares in 2100 (47% in CO2_650PPM and 59% in CO2_550PPM).

3.2 Sensitivity: Fusion investment costs

The dynamics of the model and, thus, the results for the electricity generation mix are mainly driven by the overall cost minimization. However, it is rather difficult to reliably foresee the exact cost structure of technologies in 50 or 100 years, in particular if these technologies – like fusion power – are not yet available today. Thus, we perform a so-called sensitivity analysis, namely we test the robustness of our results against variations of fusion investment costs. To this end we multiply the investment costs by constant factors in the range from 1 to 2 and subsequently evaluate our model.

The result of this analysis is shown in Figure 5 using the CO2_550PPM scenario as a basis. In fact, fusion market shares decline as investment costs increase. At the same time nuclear fission market shares only marginally increase while the component of renewable energies in the electricity generation mix fill the gap from the shrunken fusion share. This is again a consequence of the Uranium resource constraint which prevents nuclear fission from further growth. Within a likely range of fusion investment costs the fusion market share does not vary dramatically. Even in the worst case, namely with a doubling of fusion investment costs, fusion still plays a significant role. This, however, relies on severe emission targets to be met and the finiteness of the nuclear fission electricity production potential.

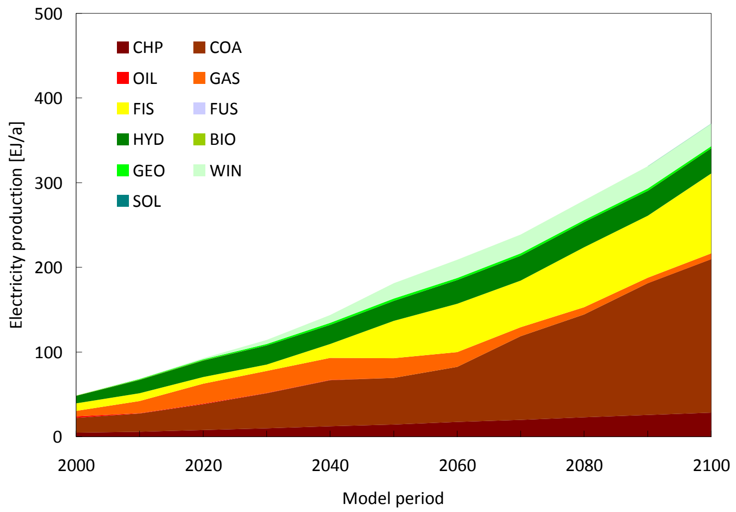

FIG. 2: Global electricity generation mix in the BAU *scenario. Combined heat and power plants (CHP) can use both fossil fuels and biomass as input.*

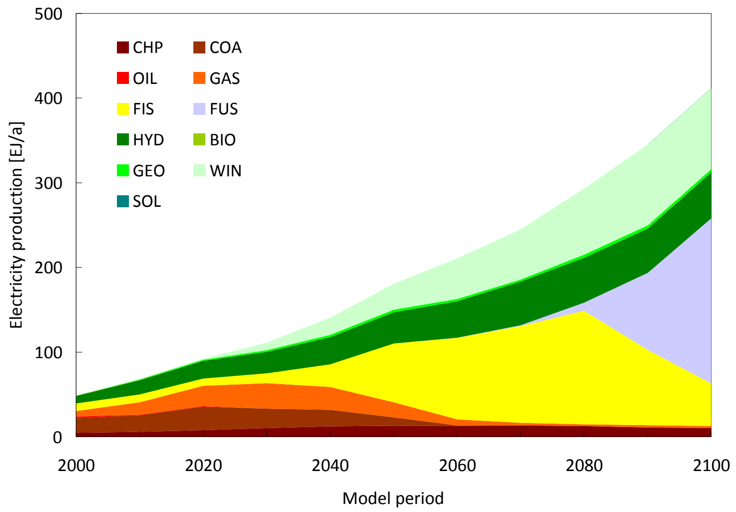

FIG. 3: Global electricity generation mix in the CO2_650PPM *scenario. Note that carbon capture and storage processes are not displayed separately.*

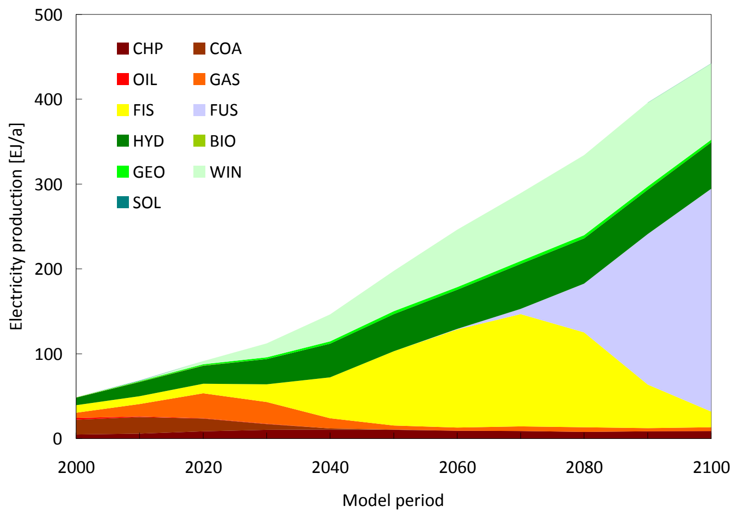

FIG. 4: Global electricity generation mix in the CO2_550PPM *scenario. Note that carbon capture and storage processes are not displayed separately.*

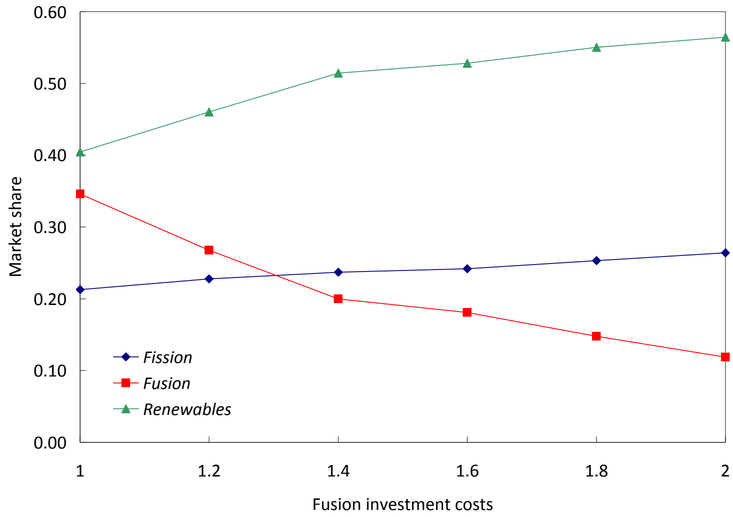

FIG. 5: Share of cumulative electricity generation by various technologies in the period from 2067 to 2104 for different values of fusion power investment costs in the CO2_550PPM *scenario.*

3.3 Sensitivity: Fission potential

The scenarios discussed so far contain a severe Uranium resource constraint equivalent to 17,500 EJ of energy extracted by means of a conventional LWR. In order to enlarge the amounts of energy generated by nuclear fission plants new technologies must be developed. Possible options are the reprocessing of burned nuclear fuel in order to enhance the overall efficiency of the nuclear fuel cycle, the use of fast breeder reactors which could also be designed such as to employ Thorium (which is much more abundant than Uranium) as a primary energy source, or even the advent of very high temperature reactors or accelerator driven systems which can be able to burn all the fissionable material or even breed more nuclear fuel from the transuranics in the nuclear waste and, thus, may also reduce the amount of long-lived waste produced. At present, however, neither one of these technologies is ready for commercial use. Thus, substantial investments in the development of these technologies are required and the costs of advanced fission power plants once available for commercial use are subject to large uncertainties.

Both nuclear fusion and nuclear fission using breeder reactors are technologies which are in principle able to satisfy the global electricity demand for far longer than one century. The markets will be driven by environmental and proliferation concerns connected to the processing of highly activated nuclear fission materials, together with the costs. However, since both environmental concerns and proliferation risks are difficult to quantify our analysis focuses on the relation of the levelized electricity generation costs. This is reflected in the following set of scenarios: The last step of our multi-stepped Uranium supply curve is enlarged in order to practically provide unlimited Uranium resources. At the same time the extraction cost for this last step is gradually increased leading to gradually increasing levelized fission electricity production costs. This is done for a certain range of electricity production costs and both fusion and fission market shares are observed.

The result of this analysis is shown in Figure 6. Even if the fast breeder technology is accepted from the environmental point of view and proliferation risks are negelcted, fusion penetrates the market if levelized fission electricity generation costs become higher than roughly 4.5 ct/kWh. At levelized fission electricity generation costs of 5 ct/kWh nuclear fusion again becomes the dominant technology in the electricity sector.

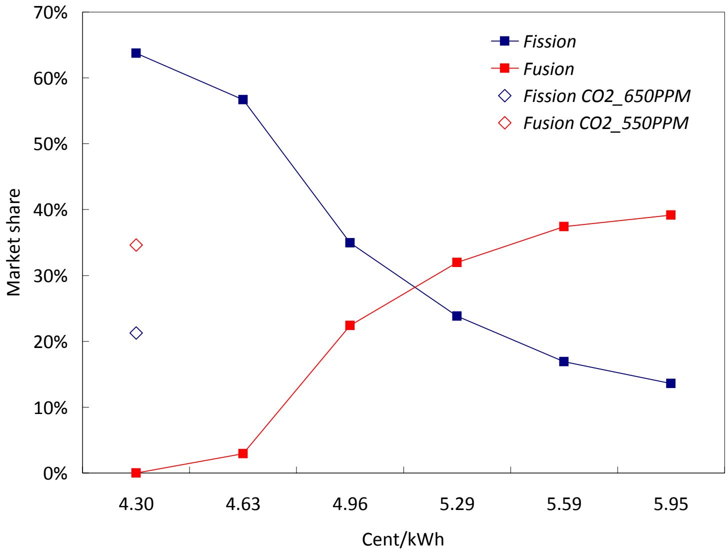

FIG. 6: Total share of cumulative fusion and fission electric power generation in the global electricity market in the period from 2067 to 2104 depending on levelized fission electricity generation costs under the assumption of unlimited Uranium resources. *The dots on the left hand side show the corresponding shares within the standard* CO2_550PPM *scenario.*

4 Summary

Figure 7 summarizes our results for a range of scenarios discussed in this article. Fusion will be able to enter the market in the second half of the century if environmental constraints will be applied consistent with a maximum atmospheric CO_2 concentration in the range of 550 to 650 ppm. This statement is valid even with a considerable increase of fusion investment costs. On the other hand, if nuclear breeders are judged to be a viable technology and proliferation risks are accepted, fusion is still competitive if levelized electricity generation costs for breeder reactors exceed those of conventional light water reactors at roughly 4.5 ct/kWh.

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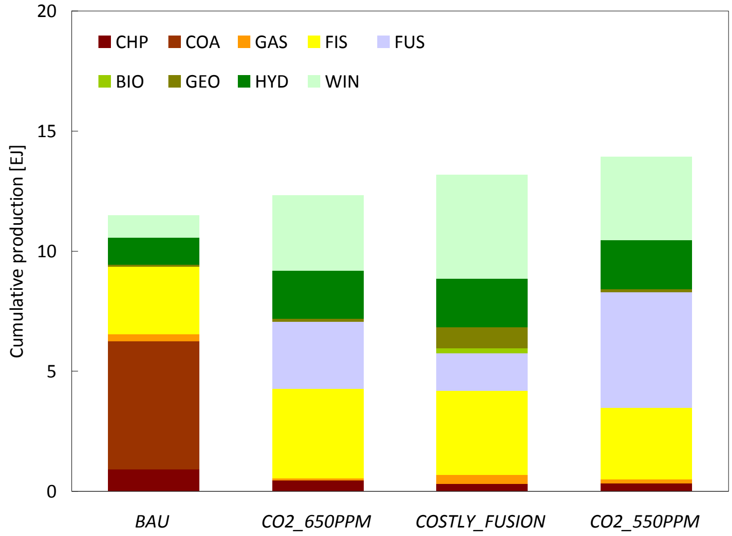

FIG. 7: Cumulative electricity generation levels in the period from 2067 to 2104 in various scenarios. Electricity produced with CCS technologies is not *displayed separately. The* COSTLY_FUSION *scenario is based on* CO2_550PPM *but assumes a doubling of fusion investments costs.*

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