Potential Role of Fusion Power Generation in a Very Long Term Electricity Supply Perspective: Case of Western Europe

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Abstract. This paper aims to explore the potential role of fusion power in future electricity supply mixes and to quantify its advantages and possible drawbacks. A general assessment of the electricity system in Western Europe is performed at its current and anticipated state, estimating generic technical and economical parameters of existing and prospective power generation technologies, and building on this basis consistent electricity markets scenarios for the time horizon 2100. Various scenarios are examined, including “reference” (without fusion) and several explorative scenarios presuming different market shares of fusion, nuclear fission and coal with CO_2 capture & sequestration. The methodology applied in this study makes use of least cost electricity systems planning model PLANELEC-Pro developed by LASEN-EPFL. It is found that deployment of total 90 GWe of fusion power in Western Europe is capable to reduce up to 10 % of the total electricity system CO_2 emissions, while causing a slight increase of the levelised electricity production cost (≈ 2-3 € / MWh). Meanwhile, nuclear fission and coal with CO_2 capture & sequestration may bring about a comparable CO_2 emission reduction, though at lower cost. It is concluded that an additional socio-economic assessment of spillover benefits of fusion technology RD&D and deployment is needed for a comprehensive analysis of the potential role of fusion power generation in future energy systems, economy and society.

1. Introduction

The controlled thermonuclear fusion is broadly recognised as one of the most prominent technical options for centralised power generation expected to become available by the mid-XXI century. Practically inexhaustible resources, inherent safety, avoidance of long-lived nuclear wastes, and significant potential for CO_2 emission reduction are among the known merits of fusion technology [1], [2]. However, under competitive electricity market environment the prospects for economic viability of fusion remain uncertain. Hence, there is a strong demand from policymakers to perform an overall techno-economic analysis of future electricity generation systems that could shed more light on the potential for market penetration of fusion power.

This paper presents the results of an ongoing study on long term electricity supply scenarios worldwide [3] implemented within the framework of the EC programme of “Socio-Economic Research on Fusion” administered by the European Fusion Development Agreement (EFDA). The main goal of the study is to estimate the potential market share of fusion power in the future electricity supply mixes, and to evaluate its advantages and possible drawbacks. More specifically the economic and environmental performances of Fusion power are being compared with the competing electricity supply options represented by nuclear fission, natural gas, coal with / without carbon capture & sequestration, and renewables.

Such a task requires elaboration of a robust analytical framework allowing for analysis and projection of multiple socio-economic and technical phenomena in their interaction. One of the possible approaches advocated in the present study consists in combining global partial equilibrium energy demand / supply model with a technology explicit bottom-up engineering model of the electricity sector. Additional inputs from energy end-use models and prospective studies could complement the picture. In this analytical framework (*Figure 1*) the electricity sector planning model PLANELEC-Pro appears to be a particularly efficient analysis tool providing necessary details on the existing and anticipated power generation technologies, as well as on the structure and modalities of operation of the electricity generation system.

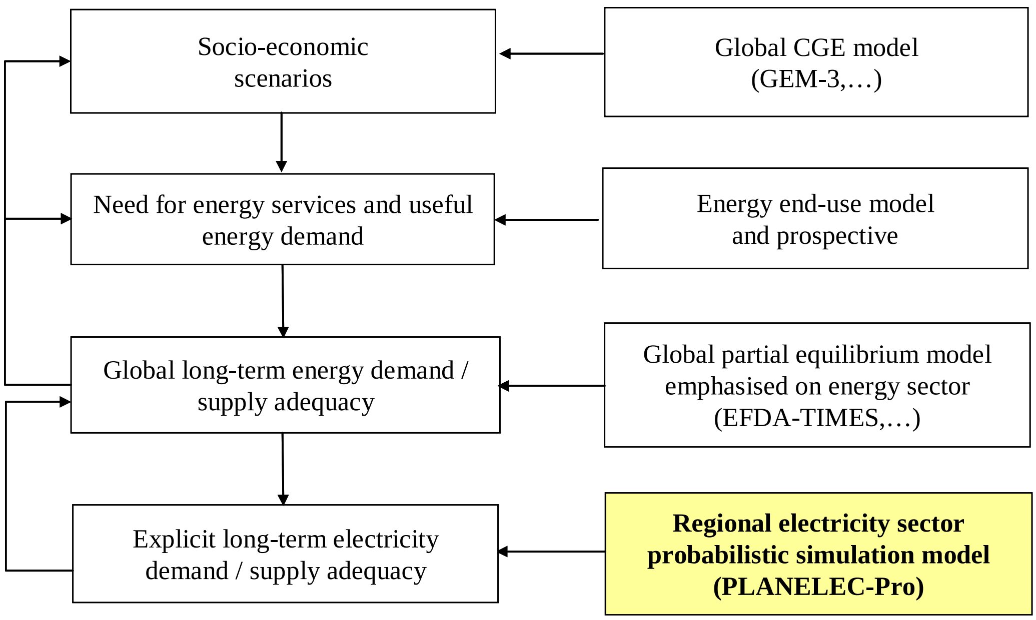


Figure 1. Analytical framework of the study

2. Methodology

The methodology applied in the present study is based on the simulation of different expansion plans of the power generation system with an objective of meeting projected future electricity demand. The study includes the following core elements:

a) Projection of long term electricity demand and supply scenarios

b) Technical and economic assessment of existing / future power generation technologies; projection of fuel prices

c) Computation of committed expansion configurations with additions of power plants of anticipated technologies

d) Economic and environmental evaluation of selected technology mixes.

An overview of the methodology is given in flowchart (*Figure 2*) stating main logical components and analysis sequences. First and foremost, the proposed methodology requires elaboration of credible scenarios of future energy markets until the time horizon 2100. For that purpose, the dominant trends and key determinant factors of energy markets development in the past should be identified, and their extrapolation in the future has to be made. Such an analysis was carried out through the review of available data on existing power generation systems, including "EURPROG" report published by the Union of the Electricity Industry (Eurelectric) [4], scenario projections of internationally renowned studies, such as IIASA / WEC "Global Energy Perspectives, 1990-2100" [5], IEA "World Energy Outlook" [6], IPCC "Special Report on Emission Scenarios" [7] , as well as on the basis of expert judgements.

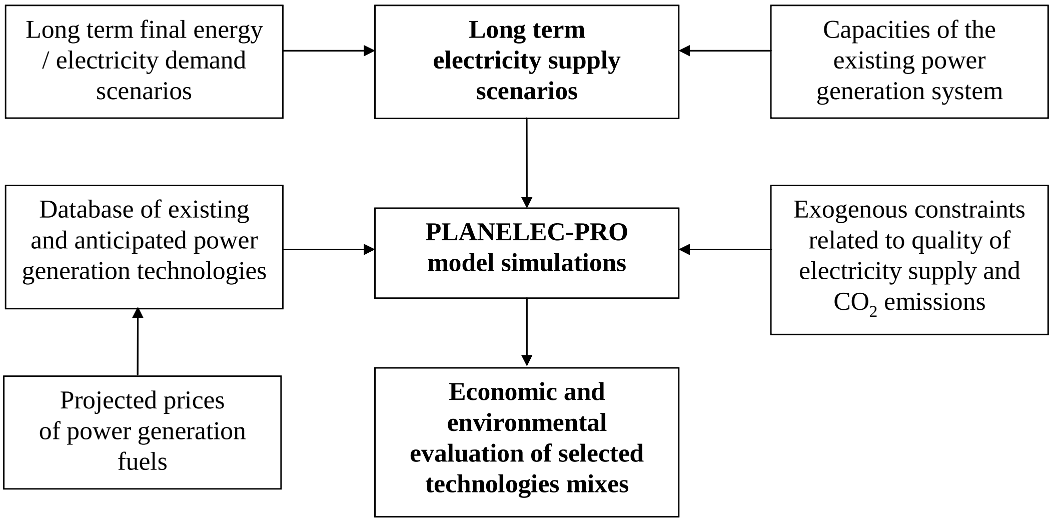


Figure 2. Methodology flowchart

Once a projection of future energy consumption and corresponding electricity demand is made, the use of a least cost planning model PLANELEC-Pro allows for determining the electricity supply mixes that meet specific criteria under environmental (CO_2), resource, and quality of service constraints. Finally, basing on the simulation of selected scenarios with PLANELEC-Pro model, increment of the total electricity generation system cost and levelised electricity production cost are assessed, as well as environmental benefits in terms of CO_2 emission reductions.

3. PLANELEC-Pro Model

3.1 Overview

The model applied in this study is PLANELEC-Pro, v.3.2, which is a least cost probabilistic simulation and dynamic programming model [8]. Given the electrical load forecasting, electricity supply quality constraints (loss-of-load probability; reserve margin) and CO_2 penalty or emission cap, the candidate power plants are selected by the model to satisfy the electricity demand together with the existing system. The objective function to be minimized is the total discounted costs including investment costs, operating and maintenance costs, fuel costs and the cost of unserved energy. The outputs of the model are optimal expansion plans concerning the number, the time and the type of power plants to be installed, total discounted cost of the expansion plan, electricity production cost, production of each plant, fuel consumption, total CO_2 emissions, CO_2 emission of each year and each type of plant, etc.

In our study the timeframe is divided into five 20-years sub-periods. Annual discount rate applied here is 5% for each sub-period relative to the first year of the sub-period. All monetary values are in Euros of year 2004. The “reference” case of system expansion without fusion and its different variants are simulated with PLANELEC model for each of the sub-periods. The simulation results of each variant are compared with those of the reference case. Main model outputs to be analysed include: levelised cost of electricity generation, total discounted cost of the expansion plan, and total CO_2 emissions. Basing on the comparison of results of different variants with reference case, additional indicators are derived, such as total CO_2 emission reduction throughout the whole study period and incremental CO_2 abatement cost for each of sub-periods.

3.2 Technology Assumptions

In accordance with EURPROG data [4], the following main types of electricity generation technologies were distinguished among the existing power plants: *Gas turbine (GT); Gas turbine operated in combined cycle (NGCC); Natural gas fired thermal power plant; Diesel engine; Fuel oil fired thermal power plant; Multifuel thermal power plant; Nuclear power plant; Hard coal fired thermal power plant; Lignite fired thermal power plant; Municipal wastes and biomass residues incinerator combined with steam turbine; Run-of-the-river hydro power plant; Reservoir accumulation hydro power plant; Pumping and storage hydro power plant; Wind power plant.* Averaged values were defined to describe technical and economic performances of the power plants of existing technologies.

Besides the existing technologies, the following main types of candidate power plants were considered: *Oil gasification GT operated in combined cycle, Supercritical pulverised coal thermal power plant, Integrated coal gasification GT operated in combined cycle (IGCC), Lignite-fired fluidised bed combustion thermal power plant, IGCC with carbon capture and sequestration (IGCC+CCS), Integrated coal gasification fuel cell operated in combined cycle, Natural gas fuelled fuel cell, Photovoltaic (PV), Wind On / Off-shore.* Detailed assumptions on main technical and economic parameters of selected candidate power plants are given in TABLE I. Average values of levelized electricity cost shown in last column do not include the costs related to electricity grid connection and grid extension.

TABLE I: SELECTED NUMERICAL ASSUMPTIONS ON TECHNO-ECONOMIC PARAMETERS OF CANDIDATE POWER PLANTS IN PLANELEC-PRO MODEL

	Efficiency	CO_2 intensity	Invest. Cost	O&M costs	Capacity factor	Average cost of electricity
	%	*tCO_2/MWh*	*€ / kW*	*€ / kW • yr*	*%*	*€ / kWh*
2000 - 2020						
NGCC	*56*	*0.36*	*550*	*29.5*	*85*	*0.034*
Nuclear Fission	*37*	-	*1872*	*54.0*	*87*	*0.032*
Coal (supercritical)	*46*	*0.77*	*1132*	*46.0*	*83*	*0.026*
Wind on-shore	-	-	*921*	*22.3*	*25*	*0.037*
PV	-	-	*4354*	*19.2*	*16*	*0.216*
2040 - 2060						
NGCC	*62*	*0.33*	*415*	*25.7*	*87*	*0.042*
Nuclear Fission	*42*	-	*1728*	*49.9*	*89*	*0.031*
Fusion	*46*	-	*6765*	*308.7*	*70*	*0.115*
Coal IGCC	*56*	*0.63*	*1037*	*52.7*	*85*	*0.028*
Coal IGCC + CCS	*50*	*0.07*	*1417*	*133.8*	*80*	*0.046*
Wind on-shore	-	-	*642*	*18.6*	*30*	*0.023*
PV	-	-	*2021*	*9.5*	*20*	*0.080*
2080 - 2100						
NGCC	*66*	*0.31*	*368*	*24.3*	*89*	*0.062*
Nuclear Fission	*48*	-	*1595*	*46.1*	*91*	*0.034*
Fusion	*50*	-	*4089*	*150.6*	*83*	*0.054*
Coal IGCC	*60*	*0.59*	*920*	*50.4*	*89*	*0.030*
Coal IGCC + CCS	*54*	*0.07*	*1183*	*110.1*	*85*	*0.043*
Wind off-shore	-	-	*751*	*35.3*	*44*	*0.020*
PV	-	-	*1104*	*7.0*	*24*	*0.038*

Source: Authors' estimation based on [9] – [16]

3.3 Assumptions on Fuel Prices

One of the main drivers of future electricity systems development will be availability and prices of power generation fuels. That issue was treated through the adoption of different scenarios regarding the shares of specific technologies / fuels in the total electricity generation / capacity installed. Meanwhile, credible assumptions on the evolution of fuel prices had to be made for the whole 100 years period considered in the study. Therefore, we have analysed the data on historical and actual prices of main fuels (crude oil, natural gas and steam coal) contained in IEA [17], [18], [19], as well as the assumptions and projections of IIASA – MESSAGE model [20] applied in quantification of B2 scenario in IPCC SRES [7]. Estimation of nuclear fission fuel cost, including the nuclear wastes management costs, was made basing on data from [21] with the provision of cost increase in long term perspective due to expected use of breeding technologies. The cost of fuel for thermonuclear fusion was assessed basing on [22] and [23]. Finally, the future price of biomass fuels was estimated on the basis of EUBIONET data [24]. The resulting projections of average fuels prices for each of the 20-years sub-period are given in TABLE II.

TABLE II: ASSUMPTIONS ON FUEL PRICES IN PLANELEC MODEL (€ 2004 / GJ)

	Hard Coal	Lignite	Fuel oil	Natural gas	Biomass	Nuclear fission	Fusion (DT + Li)
2000 - 2020	*5.84*	*5.14*	*24.13*	*14.65*	*13.24*	*4.02*	-
2020 - 2040	*9.94*	*8.75*	*34.89*	*21.99*	*15.69*	*5.58*	-
2040 - 2060	*10.48*	*9.22*	*49.15*	*27.65*	*18.68*	*7.14*	*3.57*
2060 - 2080	*12.88*	*11.33*	*55.52*	*31.90*	*18.50*	*8.70*	*4.35*
2080 - 2100	*15.27*	*13.44*	*61.89*	*36.14*	*18.32*	*10.25*	*5.13*

Source: Authors' estimation based on various studies

4. Long-Term Electricity Demand and Supply Scenarios

The scenarios developed herein are based mainly on the review of renowned international studies [5], [6], [7]. All these studies developed their own sets of scenarios which differentiate essentially on the underlying assumptions regarding future population, economic growth, primary energy and technology availability, and other factors. The projected level of energy consumption also differs significantly across different studies and scenarios. In the present work scenario "B" of IIASA / WEC study was chosen as a main reference for the projection of final energy consumption in global scale (See ***Figure 3***).

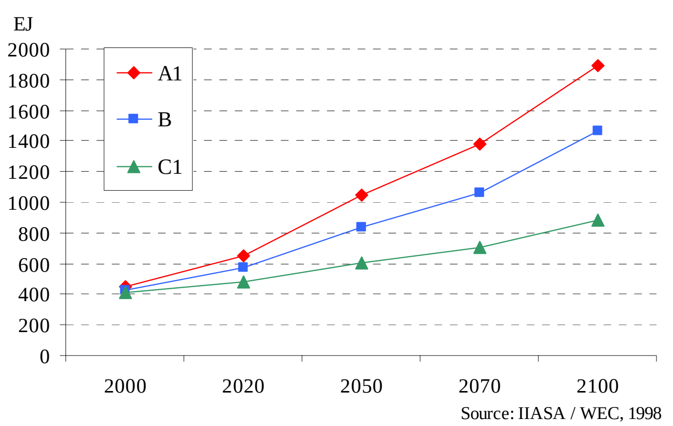


Figure 3. World final energy consumption in three scenario cases (IIASA / WEC) [5]

Basing on the estimation of final energy demand in global and regional perspective, projected share of electricity in total energy consumption, availability of primary energy fuels and other factors, the future electricity generation by fuel type was forecasted. It was observed that for the time period 2000 – 2020 the IIASA / WEC scenario “B” projections [5] noticeably differ from actual data contained in EURPROG [4]. For example, the share of natural gas in EURPROG is considerably higher (16.5% in 2000 and 39.4% in 2020) compared to IIASA / WEC scenario “B” projection (6.2% in 2000 and 10.0% in 2020). Accordingly, the share of coal in EUROPROG is significantly lower in both 2000 and 2020, and the share of nuclear power is expected to be much lower in 2020 compared to IIASA / WEC scenario “B”.

Therefore, in the elaboration of long term electricity supply scenarios for Western Europe it was decided to preserve actual and anticipated structure of power generation in accordance with EURPROG, while keeping the electricity production growth rate conforming to IIASA / WEC scenario “B” projection (see TABLE III).

TABLE III: EVOLUTION OF ELECTRICITY GENERATION IN WESTERN EUROPE

Electricity generation (TWh)	**2000**					
IIASA / WEC scenario “B”	*2859*	(forecast)				
EURPROG	*2798*	(actual)				
Annual growth rate (%)	**2000-2010**	**2010-2020**	**2020-2030**	**2030-2050**	**2050-2070**	**2080-2100**
IIASA / WEC scenario “B”	*1.5*	*1.5*	*1.5*	*1.8*	*1.0*	*1.1*
EURPROG	*2.0*	*1.9*				

Sources: [4], [5]

Given actual / forecasted structure of electricity generation by fuel type and knowing the corresponding structure of installed power generation capacities, we could calibrate the PLANELEC-Pro model’s data set and proceed to the analysis of future development paths of the electricity generation system. As a result, we have elaborated a “reference” system expansion plan and a number of its variants that were examined further in more details through the simulations with PLANELEC-Pro model.

4.1 Reference Case

According to this “Reference” case, the major contributors to the expansion of power generation system would be natural gas and renewable energy technologies. It is expected that capacity and share of renewables would grow steadily throughout the whole period of the study, reaching significant 310 GWe corresponding to approximately 21% of total projected capacity in 2100. At the same time, capacity and share of technologies based on natural gas are expected to increase only in the first half of the century, while declining after 2050 due to increase of natural gas price.

It was further projected that expansion of power generation capacities in the second half of century would be assured mainly by coal and nuclear fission technologies of advanced concept. As regards to hydro power, it is projected to increase slightly, and fuel oil power generation is expected to be completely phased out. The projected values of installed electricity generation capacities in repartition by fuel type in “Reference” case are given in *Figure 4*.

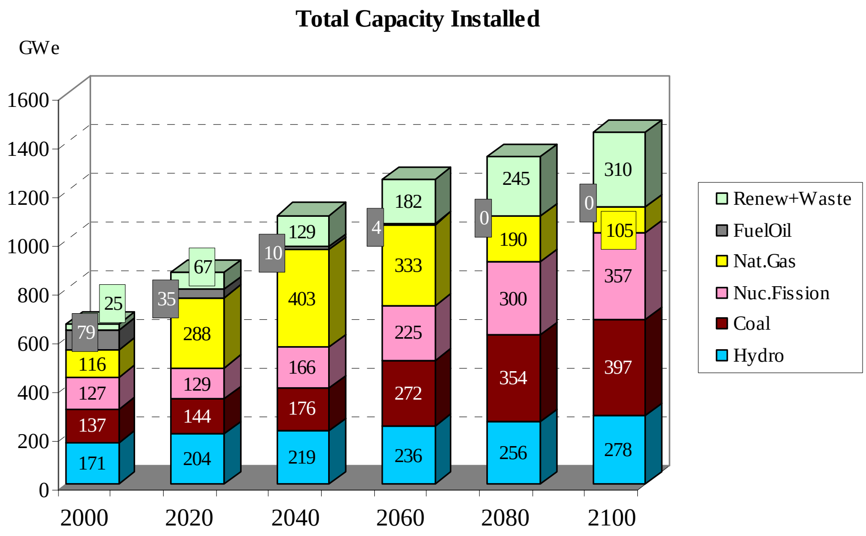


Figure 4. Projected structure of installed power generation capacities in "Reference" case

4.2 Scenario Variants

In addition to the "Reference" case, the following variants were analysed in the study:

- ***Introduction of Fusion***
  Deployment of fusion power plants in commercial scale begins during the period 2040 – 2060 reaching 6 GWe in 2060 and 42 GWe in 2080. In 2100 the installed capacity of fusion power is projected to be 90 GWe corresponding to ≈ 6.2 % of total installed capacity. Accordingly the same amounts of coal-fired power plants are being displaced from the system.
- ***Fusion (+)***
  This is an alternative case presuming massive deployment of fusion power plants. It is assumed that in 2060 capacity of fusion power would reach 9 GWe, in 2080 - 60 GWe, and in 2100 total 186 GWe of fusion capacity would be installed, again displacing the same amounts of coal-based electricity generation capacities.
- ***Coal CCS***
  This is an analogous case to the "Fusion (+)" scenario with the only difference that fusion power is substituted by the same amount of coal-fired power generation technologies with CO_2 capture & sequestration (186 GWe ≈ 12.8 % of total installed capacity in 2100).
- ***Nuclear Fission***
  This scenario is characterised by the increased amount of nuclear fission. Additional 186 GWe of nuclear fission power displaces here the same amount of coal-fired power generation (without CO_2 capture) in 2100.
- ***"CO_2 tax"***
  In addition to the set of basic scenario cases described above, we have simulated the same technology mixes applying a tax on CO_2 emission within the range € 20 - € 50 / t CO_2 .

5. Main Findings

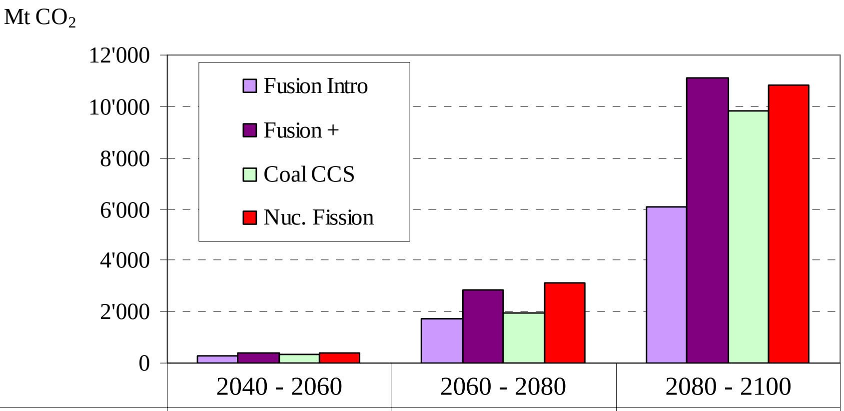
Simulation of the main scenario cases with PLANELEC-Pro model provides the following results in terms of levelised electricity production cost for each of 20-years sub-periods (TABLE IV).

TABLE IV: LEVELISED SYSTEM ELECTRICITY GENERATION COST (€ 2004 / KWH)

	Reference	**Introduction of Fusion**	**Fusion +**	**Coal CCS**	**Nuclear Fusion**
2000 - 2020	*0.034*	*0.034*	*0.034*	*0.034*	*0.034*
2020 - 2040	*0.036*	*0.036*	*0.036*	*0.036*	*0.036*
2040 - 2060	*0.036*	*0.036*	*0.036*	*0.036*	*0.036*
2060 - 2080	*0.036*	*0.038*	*0.038*	*0.037*	*0.036*
2080 - 2100	*0.035*	*0.038*	*0.039*	*0.036*	*0.036*

Source: Authors' calculation with PLANELEC model

These results show that the assumed deployment of fusion power entails a modest increase in the levelised cost of electricity generation, with the order of magnitude of € 2 - 4 / MWh. This estimation, however, depends to a great extent on the assumptions regarding technical and economic characteristics of prospective power generation technologies and fuel prices. The expected levels of the CO_2 emission reduction in different cases compared to the "Reference" case are shown in *Figure 5*.



	2040 - 2060	2060 - 2080	2080 - 2100
Fusion Intro	298	1'738	6'111
Fusion +	375	2'869	11'107
Coal CCS	323	1'943	9'832
Nuc. Fission	413	3'125	10'806

Figure 5. CO_2 emission reduction in main scenario cases

The presented values correspond to the reduction of total CO_2 emissions of the electricity generation system due to deployment and operation of technologies with lower or "zero" CO_2 emission rates. The resulting incremental CO_2 abatement cost for last 20-years sub-period (2080 - 2100) is given in TABLE V. It is calculated as the difference of the discounted total system costs in "reference" and specific cases at the end of sub-period (in 2100) divided by the difference in accumulated CO_2 emissions throughout the whole 20-years sub-period.

TABLE V: CO2 ABATEMENT COST IN 2080 - 2100

Scenario case	**Abatement cost (€$_{2004}$ / t CO_2)**
Fusion +	26.1
Coal CCS	9.4
Nuclear Fusion	4.1

Source: Authors' calculation with PLANELEC model

The results of simulation of two environmental policy regimes presuming introduction of tax on CO_2 emissions (€ 20 and € 50 / t CO_2) are given in TABLE VI.

TABLE VI: LEVELISED SYSTEM ELECTRICITY GENERATION COST UNDER DIFFERENT LEVELS OF CO2 TAX (€ 2004 / KWH)

	Reference	**Introduction of Fusion**	**Fusion +**	**Coal CCS**
€ 20 / t CO_2				
2040 - 2060	*0.041*	*0.041*	*0.041*	*0.041*
2060 - 2080	*0.041*	*0.041*	*0.042*	*0.041*
2080 - 2100	*0.040*	*0.041*	*0.043*	*0.040*
€ 50 / t CO_2				
2040 - 2060	*0.048*	*0.048*	*0.048*	*0.048*
2060 - 2080	*0.047*	*0.047*	*0.047*	*0.046*
2080 - 2100	*0.047*	*0.047*	*0.048*	*0.045*

Source: Authors' calculation with PLANELEC model

6. Conclusions

According to the results of simulations with PLANELEC-Pro model, introduction of fusion power allows for achieving substantial reduction in CO_2 emissions, equivalent to ≈ 10% of total system CO_2 emissions throughout the period 2040 – 2100 in basic case, and ≈ 17% in "Fusion (+)" scenario case. Without taxation of CO_2 emissions fusion power entails only a slight increase of the levelized electricity production cost with the order of magnitude 2 - 3 € / MWh in basic case, while massive deployment of fusion leads to a greater increase of the production cost by ≈ 4 € / MWh. Meanwhile, under stringent environmental policy regime imposed through the introduction of CO_2 tax, fusion power can be deployed without any significant welfare loss.

As regards economic performance of fusion compared to other technological options for centralised base-load electricity generation, it is found that by the end of century fusion power can become competitive compared to natural gas combined cycle, mainly due to significant increase in natural gas prices. However, it is still more expensive than nuclear fission and coal with carbon capture & sequestration technologies. It is concluded that economic viability of fusion power will depend greatly on the advancements in R&D on thermonuclear plant design and subjacent technologies that should allow for bringing down the investment cost of fusion reactor. To justify increased public expenditures on fusion R&D it is proposed to carry out a comprehensive socio-economic study of positive externality effects, also referred to as "spillover benefits" [25] of fusion research, development, demonstration and deployment programme to be implemented in a worldwide scale. Such a study should allow for evaluation of total social returns of fusion technology that could be several times higher than its private economic returns [26].

7. Acknowledgements

The present study has been implemented with the financial support of the European Communities within the framework of EFDA "Socio-Economic Research on Fusion" programme. The views and opinions expressed herein do not necessarily reflect those of the European Commission. All imperfections remain solely responsibility of the authors.

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