Nuclear Fusion as New Energy Option in a Global Single-Regional Energy System Model

C. Eherer 1), M. Baumann 1), J. Düweke 2), T. Hamacher 2)

1) Institute for Theoretical and Computational Physics (ITP), Graz University of Technology, Austria
2) Max Planck Institute for Plasma Physics (IPP), Garching, Germany

e-mail contact of main author: eherer@itp.tu-graz.ac.at

Abstract. Is there a window of opportunity for fusion on the electricity market under “business as usual” conditions, and if not, how do the boundary conditions have to look like to open such a window? This question is addressed within a subtask of the Socio-Economic Research on Fusion (SERF) programme of the European Commission. The most advanced energy-modelling framework, the TIMES model generator developed by the Energy Technology System Analysis Project group of the IEA (ETSAP) has been used to implement a global single-regional partial equilibrium energy model. Within the current activities the potential role of fusion power in various future energy scenarios is studied. The final energy demand projections of the baseline of the investigations are based on IIASA-WEC Scenario B. Under the quite conservative baseline assumptions fusion does not enter the model solution and it can be observed that coal technologies dominate electricity production in 2100. Scenario variations show that the role of fusion power is strongly affected by the availability of GEN IV fission breeding technologies as energy option and by CO_2 emission caps. The former appears to be a major competitor of fusion power while the latter opens a window of opportunity for fusion power on the electricity market. An interesting outcome is furthermore that the possible share of fusion electricity is more sensitive to the potential of primary resources like coal, gas and uranium, than to the share of solar and wind power in the system. This indicates that both kinds of technologies, renewables and fusion power, can coexist in future energy systems in case of CO_2 emission policies and/or resource scarcity scenarios. It is shown that Endogenous Technological Learning (ETL), a more consistent description of technological progress than mere time series, can have a remarkable impact on the model results.

1. Introduction

Facing the expected growth in energy demand on a global scale during the next decades, whereby especially fast growing economies in the non-OECD part of the world (e.g. China) will have an impact on the situation, the investigation of the technical and economic potential of new energy supply technologies in possible future energy systems is of high interest.

Nuclear fusion is one of the promising new energy supply technologies due to its safe operation, nearly inexhaustible resources and its potential for a CO2 emission free production of base load electricity. Fusion reactors are expected to be commercially available for power generation about the middle of the century. Due to their large unit size, they will initially serve as base load option for electricity production. The site for the fusion experiment ITER, which is the next step in fusion research and which might bring the proof of principle for nuclear fusion, is currently under decision.

Within a subtask of the Socio-Economic Research on Fusion (SERF) programme of the European Commission the central goal is to identify, whether there is a window of opportunity for fusion on the electricity market under “business as usual” conditions, and if not, how the boundary conditions have to look like to open such a window [1].

The most advanced energy-modelling framework, the TIMES model generator developed by the Energy Technology System Analysis Project group of the IEA (ETSAP) has been used to implement a global single-regional partial equilibrium energy model at the IPP Garching in co-operation with the ITP Graz [2].

Within an EFDA-SERF project task, the ITP Graz studies the potential role of fusion power in a future energy system. The work is done in co-operation with the IPP Garching and is mainly focused on long-term scenario analysis until 2100 with special attention to nuclear fusion and its most likely long-term competitors. Scenarios comprise possible development paths of major driving forces of an energy system. They can be seen as story lines formulated by the modeller or by stakeholders to assess e.g. the impact of energy policies [3].

2. Methodology

2.1. The TIMES Model Generator

The main tool to carry out the present system studies is the "The Integrated MARKAL EFOM System" (TIMES), which is the latest energy modelling framework developed by the Energy Technology System Analysis Project group of the IEA (ETSAP). TIMES is a so called model generator. The modeller provides information about the structure of the energy system, the energy technologies and all the required technical and economic data. Out of these information TIMES generates an economic model of the energy system in terms of a mathematical programme that computes a supply-demand equilibrium for the energy part of the economy (partial equilibrium) based on maximising total surplus.

In a TIMES model energy technologies are explicitly modelled in detail in terms of technological and economic data, which is a bottom-up description of the energy system. The scope of TIMES models is beyond purely energy related issues. The representation of materials and environmental emissions related to the energy system is possible. Thanks to the explicitness of the representation of technologies and fuels, a TIMES model can be constructed to analyse energy-environmental policies.

The energy system in a TIMES model is depicted by flows of energy carriers and energy technologies are modelled by the concept of a Reference Energy System (RES). Energy, material flows and emissions are described by commodities, which are transformed by processes into each other. In this way, the whole path from primary energy to final energy or even energy services can be modelled.

TIMES offers a number of advanced modelling features for a sophisticated representation of the energy system (e.g. variable model period lengths, flexible time slices and storage processes, accurate and realistic depiction of cost payments and investments, flexible processes, Endogenous Technological Learning, data decoupled from period definition, age dependent parameters, vintaging, multiple model regions linked by inter-regional trade) [4], [5], [6].

2.2 The TUG-IPP Global Energy Model

The developed global model depicts the energy system starting from extraction of primary energy carriers over conversion, refining and distribution to the various end-use sectors demanding final energy. In addition, a simplified description of the transport sector is included. At the moment, the focus of the model structure lies on the supply side (especially electricity production), while the demand side is viewed at in an aggregated way. Although, the model is single-regional at the present state, the energy demands are split into OECD and non-OECD due to the expected differences in development in these two world regions. Figure I gives an overview over the structure of the TUG-IPP model.

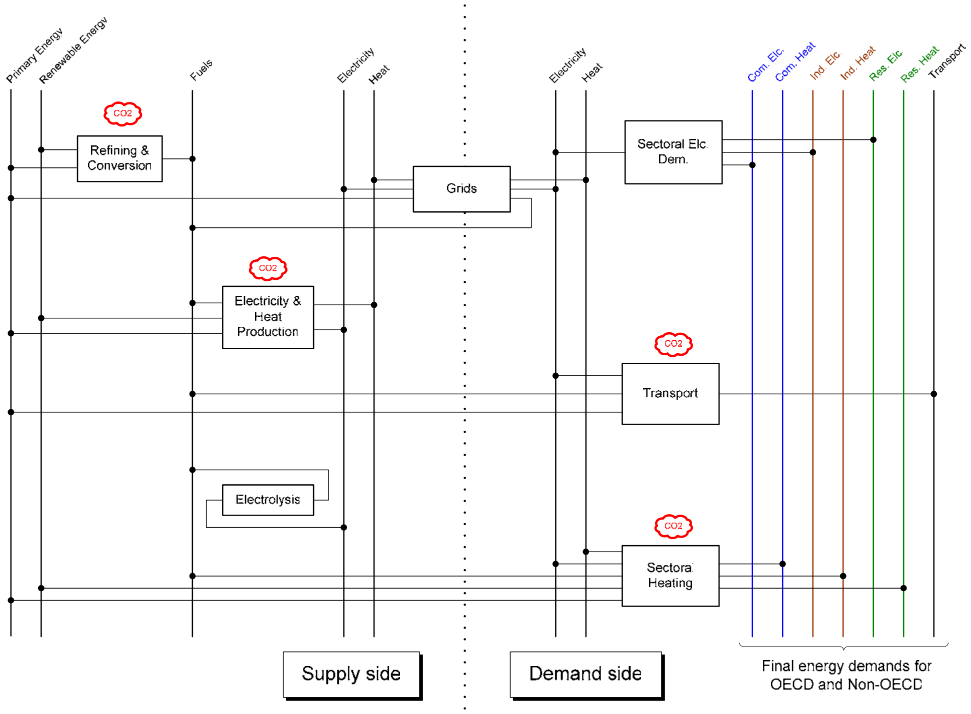

FIG. I. STRUCTURE OF THE TUG-IPP MODEL.

The time horizon of the model is the long-term future. It reaches from 1990 to 2100, divided into 12 model periods of 10 years length each. The resolution is annual, no seasonal or even smaller time divisions are made. Past investments existing prior to the model time horizon are accounted for.

The set of electricity and central heat production technologies includes a variety of present and future technology types: nuclear fusion power, nuclear fission power, coal and gas plants, CO2 sequestrating technologies, hydro power, solar thermal power, photovoltaic, on- and offshore wind turbines, geothermal power from hard dry rock and aquifers, biomass and biogas plants, fuel cell plants.

To achieve a more realistic representation of the development of a technology dynamic growth constraints are being used. Such constraints link the development of a technology in one period with its status in the previous period. In reality, the growth of a technology is dependent on its former development. So, by the use of dynamic growth constraints unrealistic effects (e.g. the taking over of the whole market in one single period, or the alternating use of two technologies) can be prevented, leading to smoother transitions from one technology to another one and smoother transitions between periods.

3. Baseline Scenario

An energy scenario consists of a set of coherent assumptions about future trajectories of the drivers of an energy system. It describes a possible way in which the future may enfold [3]. Long-term energy models like the TUG-IPP model are explorative tools for the investigation of such possible futures based on contrasted scenarios. In a TIMES model, a scenario consists of different types of inputs: energy demands, primary resource potentials (coal and lignite, natural gas, crude oil, uranium), a policy setting, and the description of a set of technologies [7].

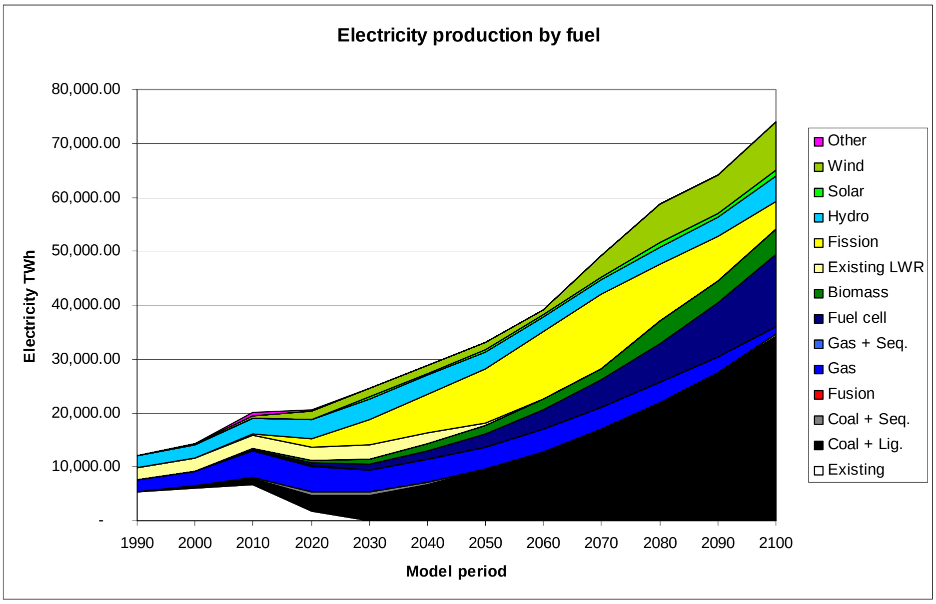

FIG. II. ELECTRICITY PRODUCTION BY FUEL

In the baseline scenario of the TUG-IPP model the final energy demands are based on the projections of IIASA-WEC Scenario B, which are characterised by moderate growth [3]. Recent numbers for primary resource potentials were included ([8], [9], [10], [11], [12]) and the maximum share of electricity generated by wind and solar power was given an upper limit of 30%. In the baseline no policies like emission caps or taxes are assumed and no GEN IV nuclear fission breeding technologies are available. Commercial fusion power plants are assumed to be available in the mid of the century. For investments a discount rate of 5% has been chosen for all model periods.

Figure II shows the results for the electricity production mix in the baseline scenario. One can observe that coal technologies without CO_2 sequestration dominate electricity production in 2100 (43%). Nuclear fission contributes quite a lot to the electricity mix (up to 30% in 2050) and starts to decline slowly about 2070 due to ongoing depletion of the uranium resources available in the baseline. Gas turbines and fuel cells satisfy the peak load demand for electricity (ca. 20% of the demand). Solar power, wind turbines, biomass plants and hydro power produce together 24% of the electricity in 2100, while fission accounts for only 7% of the production. Nevertheless, without any emission policies, the chosen development path favours inexpensive electricity from coal. In the described setting of the baseline, which is chosen quite conservative, fusion power cannot compete as base load option with coal and nuclear power.

4. Scenario Variations

To investigate the influence of different boundary conditions on the potential of fusion power a number of scenario variations have been carried out and analysed. Compared to the baseline all combinations of the following scenario assumptions have been tested: different cumulative CO_2 emission constraints leading to a certain stabilisation level [13], an upper limit on the cumulative amount of CO_2 sequestration, different upper limits on the maximum share of solar and wind power, different potentials of primary resources, existence of nuclear fission breeding technologies (Table I).

TABLE I: SCENARIO VARIATIONS.

Assumption	Variations
Cumulative CO_2 emission constraints	450 ppm / 550ppm / no limit
Maximum amount of cumulative sequestrated CO_2	300 Giga tonnes carbon / no limit
Maximum share of electricity from wind and solar power	30% / 60%
Amount of primary resources	65% / 100% / 200% (of baseline)
GEN IV Nuclear fission breeding technology	yes / no

For the analysis of key boundary conditions the total electricity produced from fusion power plants has been compared to the total cumulative production over the whole model horizon. The observations derived from the results of all possible scenario variations (in total 72 variations) can be summarised as follows.

If nuclear fission breeding technologies are available as energy option (at 30% higher investment cost, 50% higher operation and maintenance cost and 100% higher activity costs than LWRs [14]), nuclear fusion power does not enter the electricity mix in any of the scenarios. In the cases where breeder reactors are not available, fusion power can get a market share in 30 of 36 cases. In 24 of these 30 cases CO_2 emission constraints are present, confirming the expected impact of emission policies on the role of fusion power. The amount of fusion power is also dependent on the amount of primary resources and the maximum shares of wind and solar power, while the limit on cumulative sequestrated CO_2 has no impact. Furthermore, it can be seen, that the amount of resources has a higher impact on the share of fusion power than an imposed upper limit on the share of wind and solar power. The maximum share of cumulative electricity production that can be reached by fusion power in scenarios without fission breeding technologies is 12.5%.

5. Impact of Price Elastic Energy Demands

In the solution of a TIMES model the quantities and prices of the various commodities of the energy system are in equilibrium, i.e. their prices and quantities in each time period are such that at those prices the suppliers produce exactly the quantities demanded by the consumers [7]. This equilibrium is present at every stage of the energy system from primary energy forms to final energy demands. In the scenario variations presented above, the energy demands were assumed to be totally price inelastic compared to their baseline values, i.e. they would not respond to price changes of final energy at all. In reality, demands will reduce or increase compared to a reference case, when prices rise and fall, respectively.

TIMES offers the feature to make energy demands price sensitive, by assigning elasticities to them. The demands can thus self-adjust within a certain bandwidth endogenously within the model, allowing a bona fide supply-demand equilibrium. In a next step, this feature was included into the TUG-IPP model. As a point of reference and for price calibration, the baseline scenario from section 3 was chosen. The same scenario variations as described in section 4 were carried out with price elastic energy demands allowing feedback effects of prices on demands.

As expected, the results show the general behaviour in the elastic case, the total cumulative electricity production is lower than in the base case due to demand reductions, if CO_2 emission constraints are imposed on the system. Due to elastic demands, the model had the chance to balance welfare losses caused by a more expensive electricity mix with welfare losses caused by demand reductions, leading to an optimal distribution of the two with respect to the net total surplus of the system. Surprisingly, demand reductions are not correlated with the presence of a maximum bound on sequestrated CO_2.

Concerning the role of fusion power the picture is comparable to the non-elastic case. Fusion gets again no market share if fission breeder reactors are available in the technology mix under the cost assumptions made above. In the scenario variations without fission breeding technologies, fusion gets a higher share on total electricity production only with imposed CO_2 emission caps, or in case of a low share of renewables and less primary resources than in the base case. The maximum share of cumulative electricity production that can be reached by fusion power in scenarios including demand elasticity without fission breeding technologies is 14.2%.

6. Impact of Endogenous Technological Learning

In long-term energy models, one of the important issues is to describe the future development of the technological progress. Among the parameters that are important for the characterisation of a technology are the specific investment costs [15]. Some years ago, in energy models the cost development was considered as being a function of time, i.e. a technology becomes cheaper with elapsing time, also if it is not used. The progress of a technology was an exogenous assumption, though based on historic experiences. This sometimes led to unreasonable results, especially in perfect foresight models. In these models, a technology was chosen because of its competitive price in model periods at the end of the time horizon, without being in use before.

Historical experience has shown that the progress of a technology is related to the knowledge accumulated through the construction or use of this technology [16], [17]. Thus, it has become more common to treat the technological progress of a technology in an energy system model in an endogenous way.In the TIMES model generator technological learning is endogenised by linking the specific investment costs of a technology to its cumulative installed capacity via the Experience Curve concept [18], [19]. This feature has been applied the electricity producing technologies and the impact on the baseline presented in section 3 was investigated.

Figure III shows the impact of Endogenous Technological Learning on the baseline electricity production mix. Although fusion still cannot enter the baseline, the shares of other technologies change quite considerably due to the cost decreases induced by learning effects. For instance, geothermal power plants (hard dry rock, labelled “other” in the figure) and solar thermal power plants can gain a higher market share in 2100 due to a higher learning rate than e.g. coal technologies. In the baseline only solar thermal plants are built, while with ETL also photovoltaic cells gain a market share. Also gas and sequestration technologies are able to get a market share due to learning effects. This shows that ETL, which is a more consistent description of technological progress than mere time series, can influence results quite remarkably. Nevertheless, a major drawback of ETL is the tremendous increase of computer resources if one wants to include more than a few (5-10) learning technologies in an energy model.

7. Conclusion/Outlook

Under the quite conservative baseline assumptions fusion does not enter the model solution and it can be observed that coal and gas technologies account for a large part of the electricity production in 2100. Scenario variations show that the role of fusion power is strongly affected

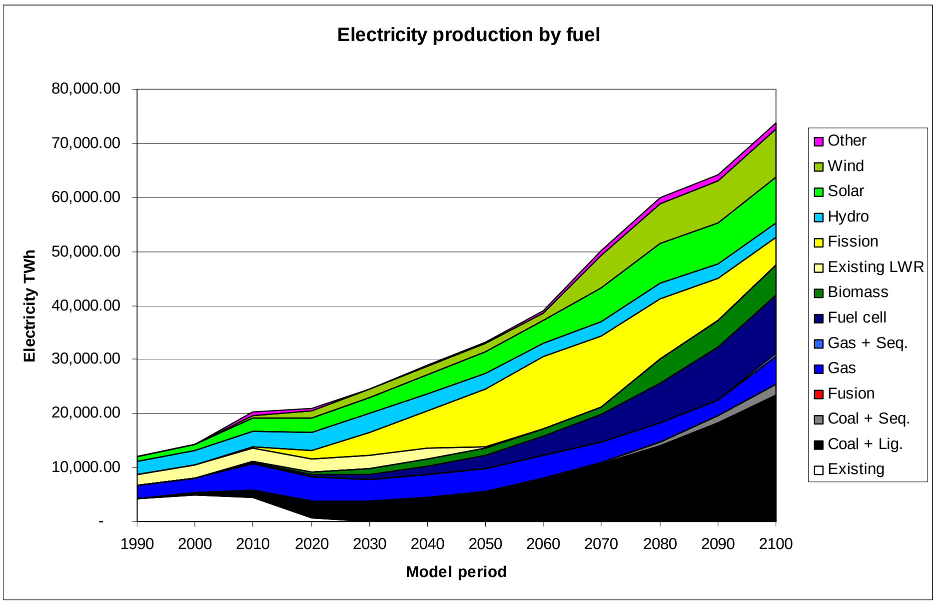

FIG. III. IMPACT OF ETL ON THE ELECTRICTY MIX IN THE BASELINE SCENARIO

by the availability of GEN IV fission breeding technologies as energy option and by CO_2 emission caps. The former appears to be a major competitor of fusion power while the latter opens a window of opportunity for fusion power on the electricity market. An interesting outcome is furthermore that the possible share of fusion electricity is more sensitive to the potential of primary resources like coal, gas and uranium, than to the share of solar and wind power in the system. This indicates that both kinds of technologies, renewables and fusion power, can coexist in future energy systems in case of CO_2 emission policies and/or resource scarcity scenarios.

It was shown that Endogenous Technological Learning (ETL), a more consistent description of technological progress than mere time series, can have a remarkable impact on the model results. The application of ETL imposes high needs on computer resources, even in case of just a few learning technologies.

In the next phase of the activities, more in depth analyses and informative results will be obtained making use of the new long-term multi-regional global energy model, which is being implemented under EFDA contract and will be released in October 2004 [7], [20]. The TUG-IPP model will be used and maintained further for quick checks, comparisons and exploration of modelling features that are only applicable in smaller models because of computer resources.

8. Acknowledgements

Besides the Austrian EURATOM Association and EFDA, we especially would like to thank the Friedrich Schiedel Foundation for Energy Technology and the Austrian Ministry of Science (BM:BWK) for their significant support of this research project.

9. Disclaimer

This work, supported by the European Communities under the Contract of Association between EURATOM and the Austrian Academy of Sciences, was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Appendix 1: References

[1] EFDA-STAC, 2004. “Fusion Technology work programme 2005”.

[2] Eherer, C., Baumann, M., Long-Term Technology Based Modelling with TIMES, Interim Report, EFDA/SERF sub task TW3-TWE-FESA/A, Garching, June 2004

[3] Nakicenovic, N., Grübler, A., and McDonald A., Global Energy Perspectives, Cambridge University Press, Cambridge, UK, 1998.

[4] TIMES, The "New" ETSAP E3 MODEL System Documentation, Working Paper, The IEA-ETSAP TIMES Working Group, 2000.

[5] Mäkelä, J., Development of an Energy System Model of the Nordic Electricity Production System, Master Thesis, Helsinki, 2000.

[6] Eherer, Ch., Fusion as a new energy technology in a long-term TIMES model of the energy system, Friedrich Schiedel project, project report, Graz-Garching, 2004.

[7] Haurie, A., Kanudia, A., Loulou, R. van Regemorter,D. and K. Vaillantcourt. 2004. “The EFDA World Model. Draft Final Report prepared for EFDA” ORDECSYS, HALOA/KANORS and KUL.

[8] BGR, Reserven, Ressourcen und Verfügbarkeit von Energierohstoffen 2002, Rohstoffwirtschaftliche Länderstudien Heft XXVIII, Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover 2003.

[9] Erdmann, G., Wirtschaftliche Vorraussetzung der energetischen Nutzung von Biomasse, TU Berlin, 1998.

[10] Fischer, G., Schrattenholzer, L., Global Bioenergy Potentials through 2050, Biomass & Bioenergy 20, pages 151-159, 2001.

[11] Kaltschmitt, M, Hartmann, H., Energie aus Biomasse – Grundlagen, Techniken, Verfahren, Springer Verlag, Berlin-Heidelberg, 2001.

[12] Lako, P., Eder, H., de Noord, M., Reisinger, H., Hydropower Development with a Focus on Asia and Western Europe, Overview in the framework VLEEM 2, ECN report C—03-027, Netherlands,. 2003.

[13] IPCC, 2000. “Special Report on Emissions Scenarios” Nakicenov, Nebojsa and Swart (eds). Cambridge University Press.

[14] Mooz, W.E., Siegel, S., A Comparison of the Capital Costs of Light Water Reactor and Liquid Metal Fast Breeder Reactor Power Plants, Prepared for the U.S. Arms Control and Disarmament Agency, R-2441-ACDA, The Rand Corporation, 1979.

[15] Bareto, L., Technological Learning In Energy Optimisation Models And Deployment Of Emerging Technologies, Dissertation, ETH Zürich, 2001.

[16] Dutton, J., Thomas, A., Academy of Management Review – Treating Progress Functions as a managerial Opportunity, Academy of Management Review Vol. 9, No.2, 235-247, 1984.

[17] Argote, L., Epple, D., Learning Curves in Manufacturing, Science Vol. 247, Febr. 1990.

[18] Wene, C., Experience Curves for Energy Technology Policy, IEA, Paris, 2000.

[19] Neij, L., et.al., Experience Curves - A Tool for Energy Policy Assessment, Lund, 2003.

[20] Lechon, Y., Cabal, H., Varela, M., Saez, R., Eherer, C., Baumann, M., Düweke, J., Hamacher, T., Tosato, G.C., A Global Energy Model with Fusion, contribution submitted to the SOFT conference, Venice, Italy, 2004.