Studies of Nuclear Fusion Energy Potential Based on a Long-term World Energy and Environment Model

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Abstract. This study investigates introduction conditions and potential of nuclear fusion energy as energy supply and CO_2 mitigation technologies in the 21st century. Time horizon of the 21st century, 10 regionally allocated world energy/environment model (Linearized Dynamic New Earth 21) is used for this study. Following nuclear fusion technological data are taken into consideration: cost of electricity (COE) in nuclear fusion introduction year, annual COE reduction rates, regional introduction year, and maximum regional plant capacity constraints by maximum plant construction speed. We made simulation under a constraint of atmospheric CO_2 concentration of 550 parts per million by volume (ppmv) targeted at year 2100, assuming that sequestration technologies and unknown innovative technologies for CO_2 reduction are available. The results indicate that under the 550ppm scenario with nuclear fusion within maximum construction speed, 66mill/kWh is required for introducing nuclear fusion in 2050, 92 mill/kWh in 2060, and 106 mill/kWh in 2070. Therefore, tokamak type nuclear fusion reactors of present several reactor cost estimates are expected to be introduced between 2060 and 2070, and electricity generation fraction by nuclear fusion will go around 20% in 2100 if nuclear fusion energy growth is limited only by the maximum construction speed. CO_2 reduction by nuclear fusion introduced in 2050 from business-as-usual (BAU) scenario without nuclear fusion is about 20 % of total reduction amount in 2100. In conclusion, nuclear fusion energy is revealed to be one of the candidates of energy supply technologies and CO_2 mitigation technologies. Cost competitiveness and removal of capacity constraint factors are desired for use of nuclear fusion energy in a large scale.

1. Introduction

Nuclear fusion energy research and development (R&D) has been made for a long term. Several fusion power reactor designs are proposed and economic evaluations have been carried out. Life cycle analysis of CO_2 emission due to construction and operation of fusion power reactors are also evaluated[1)]. Economy and environmental compatibilities of tokamak fusion power reactors have already been studied. No research has been made, however, on how much the fusion energy can contribute in the 21st century in terms of both energy supply and CO_2 mitigation. Future demands of necessity of fusion energy are to be made clear because lead-time of fusion energy application is longer than those of other energy technologies and CO_2 mitigation technologies. This study is a trial reply to such a demand.

2. Analytical Methodologies

2.1 Energy/Environment model LDNE21

A long-term, world energy and environment model is used for this study. The model name is Linearized Dynamic New Earth 21 [2] (LDNE21) with 10 regional allocations (see Fig.1) and 10-year time intervals in the 21st century. This model treats various energy supply technologies and CO_2 mitigation technologies, and illustrates contributions of the technologies by minimizing total energy systems cost under carbon emission constraints. Energy flow is modeled and calculated in order to satisfy given regional final energy demand (by solid, liquid, gas, and electricity). Given reference future energy demand is IPCC IS92a scenario. The modeled energy flow includes production of primary energies, world trades/transportations of energy goods, energy conversions (chemical plants and electricity generations), and energy conservation in end-use sectors. Secondary liquid energies such as hydrogen/methanol and CO_2 recoveries/sequestrations are also taken into account. Supplied electricity from fossil fuel combustions, renewables, and nuclear fission, are allocated through a load duration curve.

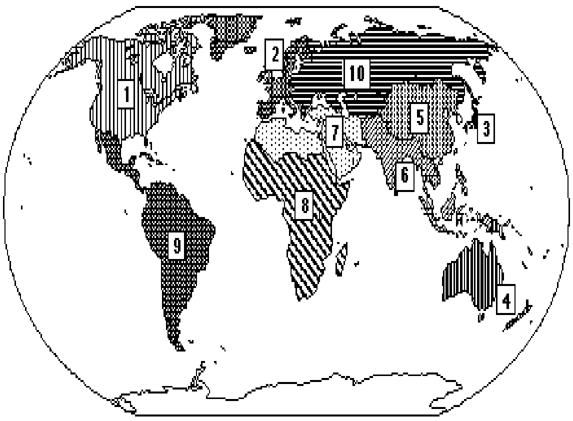

FIG.1. World Regional Allocation

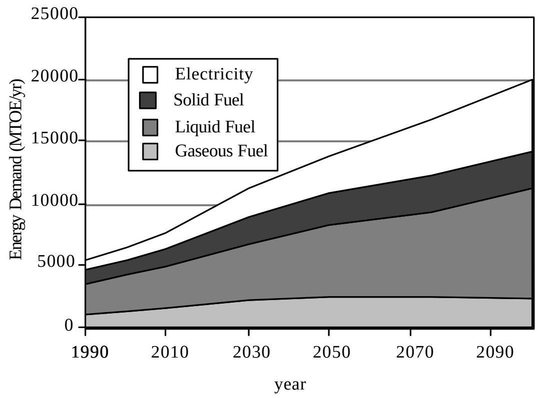

FIG.2. Given reference energy demand scenario based on IPCC IS92a

2.2 Nuclear Fusion Treatment

Technological properties of nuclear fusion are given to the LDNE21 model so as to suit for the model structure. Following parameters are given to the model: cost of electricity (COE) in nuclear fusion introduction year (introduction COE), two annual reduction rates of COE, regional introduction year, and regional capacity constraints by maximum nuclear fusion plants construction speed.

The introduction COE of nuclear fusion reactor is changed as variable to see whether introduction of nuclear fusion occurs within the maximum nuclear fusion plants construction speed. The annual reduction rates (treated as fixed parameters) are made from a COE projection (see Fig.3) of 1 GWe class tokamak type, base load operated fusion power reactors, whose COE of 101 mill/kWh, plant availability of 60%, and operation cost fraction to total capital cost of 4% in nuclear fusion introduction year. We assumed three cost reduction factors according to reactor operation experiences and technological learning after introducing fusion power reactors during 25 years. Plant availability of 78% (18% increase from introduction year) and 2% operation cost fraction (2% reduction) are assumed for reactor operation experiences. Total capital cost reduction of 20% by plant construction technological learning is assumed. Only plant availability increment (up to 83%) is assumed for further next 25 years (from 25 to 50 years after the introduction year). The two annual COE reduction rates (2.3%/yr for first 25 years, 0.25%/yr for another 25 years) are set according to these cost reduction factors.

Nuclear fusion are assumed to be introduced first in North America, West Europe, Japan and Former Soviet Union (regions 1,2,3, and 10 in Fig.1, respectively); and 20 years delay from these regions in China, South & East Asia, Africa, and Latin America (5,6,8, and 9 in Fig.1). This delay, which is assumed from world fission introduction experiences, is fixed when the nuclear fusion introduction year of North America, West Europe, Japan and Former Soviet Union is varied for survey of introduction conditions. We assume that nuclear fusions are not required in Middle East and Oceania regions where primary energy resources are abundant. This assumption is compatible with that for nuclear fission in the LDNE21 model.

Nuclear fusion and its power plant construction industries are assumed introduced according to electricity demand increase after 2050 within maximum construction speed. World total nuclear fusion electricity capacity increase is set as 100 GW/yr, which value is a little larger than that assumed from reference energy scenario (IS92a, see Fig.2). This value is divided in proportion to the regional electricity demand increase. The divided values, called maximum construction speed in this study, are used as regional nuclear fusion plant capacity growth constraints. Figure 4 shows the constraints with regional introduction scenarios.

We mainly simulated atmospheric CO_2 concentration of 550 parts per million by volume (ppmv) targeted at year 2100. This 550ppm concentration includes following two constrains to the Annex-I countries: one is Kyoto COP3 Protocol constraint at 2010, the other is 20 % CO_2 reduction among Annex-I parties from 1990 level-CO_2 emission after 2020. Moreover, in this case, we assumed two technical options can be utilized: one is terrestrial/ocean sequestration options from Integrated Gasification Combined Cycle (IGCC) power plant with CO_2 recovery, the other is innovative but unknown future technology options such as space satellite power station whose energy supply scenario is exogenously given to the model.

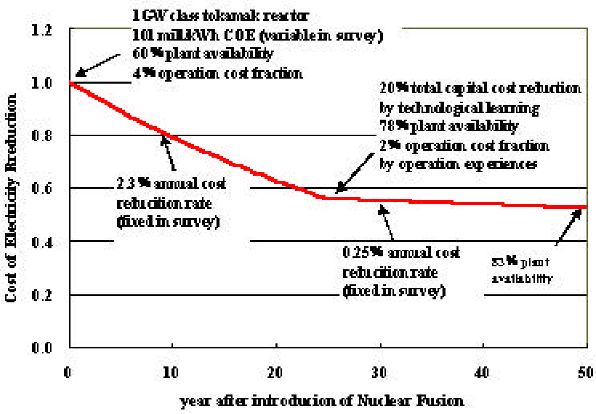

FIG.3. Assumed COE reduction projection

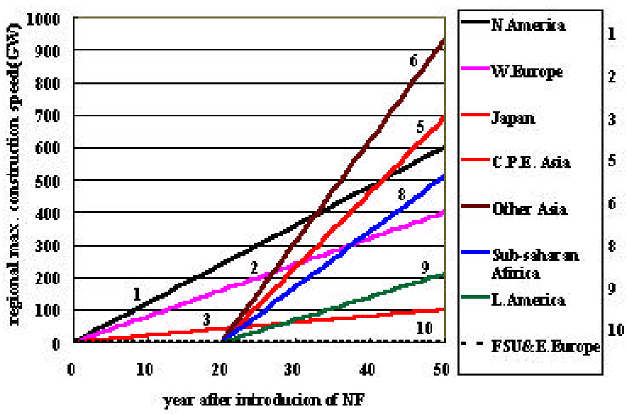

FIG.4. Given regional constraints

3. Results

Introduction COE for each introduction year is surveyed so that nuclear fusion introduces within the regional maximum construction speeds constraints. Figure 5 is the result of a case of introducing nuclear fusion in 2050 and introduction COE of 66 mill/kWh. This COE value is required otherwise the constraints are not satisfied and introduction year is considered to be delayed in a larger introduction COE. This figure shows world total electricity output under the 550ppm scenario with nuclear fusion and indicates that nuclear fusion can supply about 30% of total electricity output in 2100.

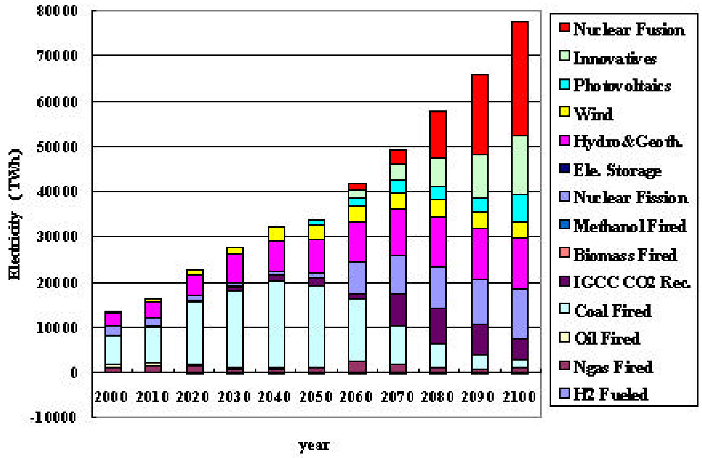

FIG.5 World total electricity output of introduction COE of 66 mill/kWh, introduction year of 2050

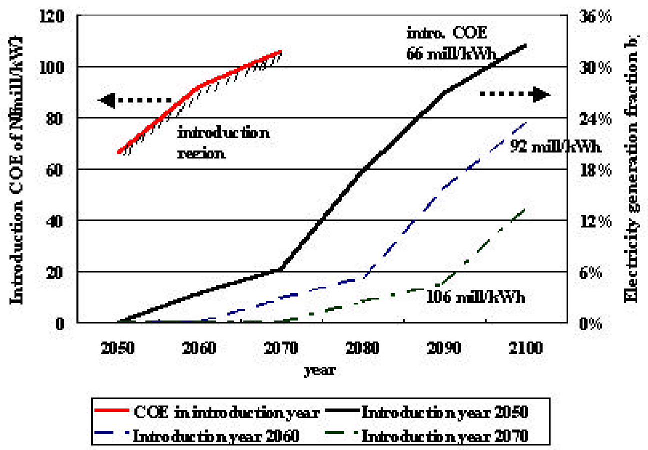

FIG.6 Relation among introduction year, introduction COE and electricity generation fraction.

Figure 6 shows required introduction COE and profiles of electricity generation fraction by nuclear fusion in the cases of introducing in the years 2050, 2060 and 2070. As seen in the left axis of the figure, introduction COE as a criterion for introducing of nuclear fusion is expressed as a function of introduction year. The profiles of electricity generation fraction for each introduction year are expressed in the right axis as a function of year. For example, introduction COE of 66 mill/kWh required in 2050 (in the left axis) and electricity production fraction readable in Fig.5 (in the right axis) are indicated. Results also indicate that 92 mill/kWh is required in 2060 (electricity production about 24% in 2100), 106 mill/kWh in

2070 (about 14%), and that present tokamak type nuclear fusion reactors are expected be introduced from 2060 to 2070 and electricity generation fraction will go around 20% in 2100.

Figure 7 indicates that CO_2 reduction by nuclear fusion (same case of Fig. 5) from business-as-usual scenario without nuclear fusion is about 20% of total reduction amount in 2100. Nuclear fusion is expected to be one of the candidates of CO_2 mitigation technologies.

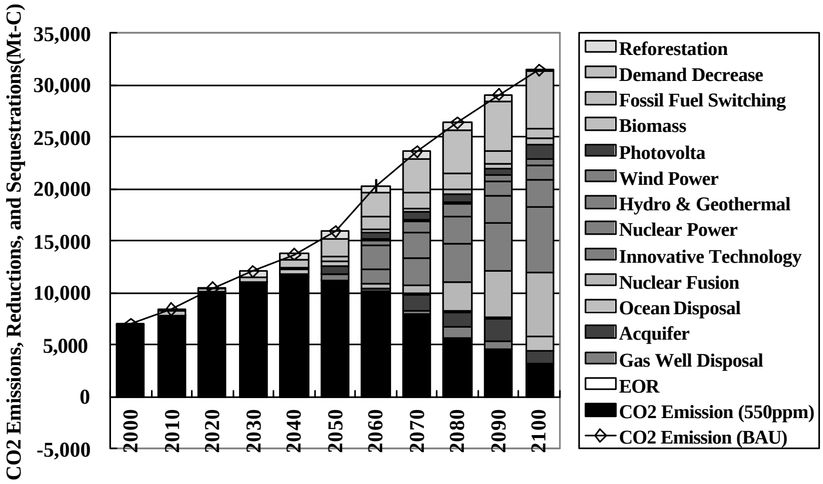

FIG.7 CO_2 reduction by nuclear fusion from business-as-usual scenario without nuclear fusion

4. Summary and Conclusion

It is revealed that under the 550ppm constraint within the maximum construction speed, 66 mill/kWh is required in 2050 (about 30% electricity production, 20% of the total CO_2 reduction from business-as-usual scenario without nuclear fusion; in 2100, respectively), 92 mill/kWh in 2060 (about 24%), 106 mill/kWh in 2070 (about 14%) Present tokamak type nuclear fusion reactors can be introduced between 2060 and 2070, and electricity generation fraction will go around 20% in 2100. In conclusion, nuclear fusion energy is revealed to be one of the candidates of energy supply technologies and CO_2 mitigation technologies. Cost competitiveness and removal of capacity constraint factors are desired for use of nuclear fusion energy in a large scale.

Acknowledgement

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1) K.Tokimatsu et. al., ”Evaluation of CO_2 emissions in the life cycle of tokamak fusion power reactors”, IAEA-CN-69/FTP-40, in proc. of 17th IAEA Fusion Energy Conference, Yokohama, October 1998.
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