Evaluation of economical introduction of Nuclear Fusion based on a Long-term World Energy and Environment Model

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Abstract

Debates about whether or not to invest heavily in nuclear fusion as a future innovative energy option have been made within the context of energy technology development strategies. The timeframe by which nuclear fusion could become competitive in the energy market has not been adequately studied, nor has roles of the nuclear fusion in energy systems and the environment. The present study has two objectives. One is to reveal the conditions under which nuclear fusion could be introduced economically (hereafter, we refer to such introductory conditions as breakeven prices) in future energy systems. The other objective is to evaluate the future roles of nuclear fusion in energy systems and in the environment. Here we chose two roles that nuclear fusion will take on when breakeven prices are achieved: i) reduction of annual global total energy systems cost, and ii) mitigation of carbon tax (shadow price of carbon) under CO_2 constraints. Future uncertainties are key issues in evaluating nuclear fusion. Here we treated the following uncertainties: energy demand scenarios, introduction timeframe for nuclear fusion, capacity projections of nuclear fusion, CO_2 target in 2100. From our investigations, we conclude that the presently designed nuclear fusion reactors may be ready for economical introduction into energy systems beginning around 2050 - 2060, and we can confirm that the favorable introduction of the reactors would reduce both the annual energy systems cost and the carbon tax (the shadow price of carbon) under a CO_2 concentration constraint; however, latter introduction of them decreases the cost and the tax less than five times. Earlier introduction of nuclear fusion reactors are desirable for energy systems and environment.

1. Introduction

There has been a growing demand for studies to assess nuclear fusion so that the potential of the technology can be realized. This is because even though extensive investments in nuclear fusion are necessary in order to develop the technology, the prospects of nuclear fusion are quite uncertain and the investments therefore carry the risk of quite large regrets. These prospects will be affected by the economic aspects of nuclear fusion, technological attributes, physical and technical realization, the timeframe for market penetration through economic competitiveness, and the roles of nuclear fusion as an innovative technology in energy and the environment. Recent studies have revealed the economical and technological attributions of nuclear fusion [1-3)]. What has not, however, been revealed thus far is the possible year in which the technology will be economically competitive in the energy market, or the roles that nuclear fusion will have in energy and environment.

2. Analytical Methodologies

Long-term (during 21st century), worldwide (10 regions division) energy/environment model linear-version of DNE (Dynamic New Earth 21), called LDNE[4)]is used for this study. This model can treat various energy supply and environmental technologies/options, and can illustrate contributions of the technologies by minimizing total energy system cost under carbon emission constraint scenarios. Energy flow from mining of primary energies, world energy goods trades and transportations, energy conversions (chemical and electricity generations), to energy conservation in end-use sector, is calculated in order to satisfy given final energy demand (solid, liquid, gas, and electricity). Electricity supply technologies such as fossil fuel combustions, renewables, and nuclear (fission), are allocated through load duration curve.

Analytical methodology is following. First, we give scenarios such as costs of electricity (COEs) and capacity projection including tritium treatment of nuclear fusion to energy and environmental model. Next, we investigated breakeven prices of the nuclear fusion based on the cost data given in the model via parameter survey under varieties of the uncertainties. Then the obtained breakeven prices are compared with COEs of the present-day designed tokamak-type fusion reactors. By this process, introductory condition of nuclear fusion, timing of tokamak-type nuclear fusion will be economically introduced into energy market, and the future roles of nuclear fusion in energy systems and in the environment are evaluated.

Nuclear fusion technological data, tokamak type as reference, are given to the LDNE model so as to suit for the model structure. Followings are taken into consideration in the same way as of the previous study[3)]; cost of electricity (COE), cost reduction rate, plant availability, tritium doubling time, maximum regional plant capacities, and regional introduction year. Tritium treatment that cannot be taken into consideration in the previous study[3)] is considered for introduction scenario of nuclear fusion, referred from a study by Asaoka et. al.[5)].

We assumed that the world total increase in nuclear fusion electricity capacity is set about 100 GW/yr of which value can be attained by future nuclear fusion plant construction industries. Nuclear fusion plants construction industries are assumed to be introduced according to the increase in demand for the reactors. The set value is divided in proportion to the increase in regional electricity demand. The divided values, here called regional maximum construction speeds, are used as regional nuclear fusion plant capacity growth projections. We set a default nuclear fusion projection, here called the initial introduction projection (IIC), which assumes nuclear fusion is introduced gradually during first 20 years with increasing plant capacity, and then constructed within the regional maximum construction speeds. This default case contains the regional growth projections and constraints of tritium breeding for nuclear fusion. The constraints are referred to as the initial quantity of tritium needed to build successive fusion power plants after the initial one is completed [5)]. The regional projections were developed specifically for the present study as same procedure of the reference[5)] but are independent from those found in the reference; the difference is that the initial tritium inventory for a first-of-its-kind fusion reactor can be assumed to be available in each region and that subsequent tritium inventory for subsequent reactors must be bred in the nuclear fusion reactors.

The following four major factors are considered for simulation. First, the year nuclear fusion is introduced; second, future nuclear fusion projection scenarios; third, variations of CO_2 concentration constraints; and fourth, future energy demand scenarios. We assumed four different introduction years of nuclear fusion: 2050 (default), 2060, 2070, and 2080. We assumed three projection scenarios for nuclear fusion; two are with/without tritium constraint (the former corresponds to IIC described above; the latter to MCS investigated in the previous study[3)]), the last is with no constraints named NC. We calculated mainly two future CO_2 emission trajectories; one is business-as-usual (BAU) case that has no CO_2 concentration constraints, the other is a constraint of atmospheric CO_2 concentration of 550 parts per million by volume (ppmv) targeted at year 2100. Uncertainty for future energy demand scenario is also surveyed. The IS (International Standard)-92a is medium, SRES (Special Report on Emissions Scenarios)-A1 is the highest, and SRES B1 is the least in levels of energy demand.

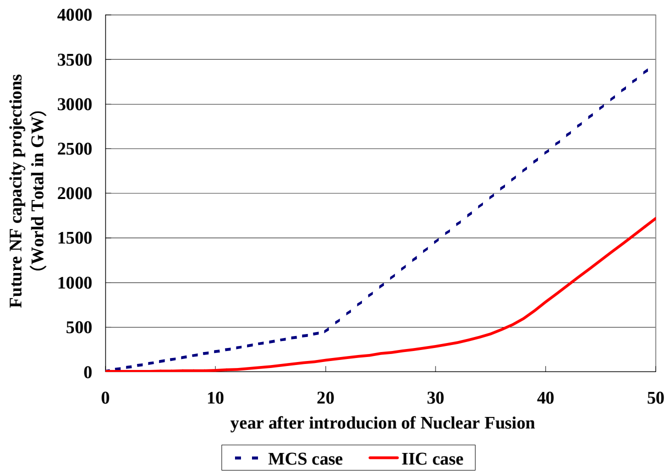

FIG 1. Assumed world future nuclear fusion capacity projection

3. Results [6)]

Figure 2 indicates the range of breakeven prices of nuclear fusion as a function of the year nuclear fusion is introduced. “BAU region” and “550-ppmv region” indicates the uncertainty range of breakeven prices in the case of the BAU and the 550-ppmv concentration constraint, respectively. Therefore according to the cost bases of the LDNE model, if the COE of nuclear fusion is less expensive than the lower line of the region, the nuclear fusion reactor can be economically introduced; however, nuclear fusion reactors whose COEs are above the upper line cannot be economically selected. The COE range of tokamak-type nuclear fusion reactors as presently designed is around 70-130 mill/kWh. Therefore, the present-design tokamak-type reactors can be economically selected around 2050 to 2060 under 550-ppmv CO_2 concentration constraint, and are not under all BAU. It is revealed that breakeven prices of fusion reactors is increased by plus/minus some 10 to 30 mill/kWh under a 650-ppmv.

Figure 3 provides the annualized cost reductions in total energy systems realized by nuclear fusion, in the same fashion as in Figure 2, assuming the 550-ppmv CO_2 constraint. The annualized total system cost is obtained by assuming annualization with a discount rate of 5 % for 100 years from the calculated discounted total energy systems cost. The horizontal axis of Figure 3 is obtained by the difference between the cost with and the cost without nuclear fusion.

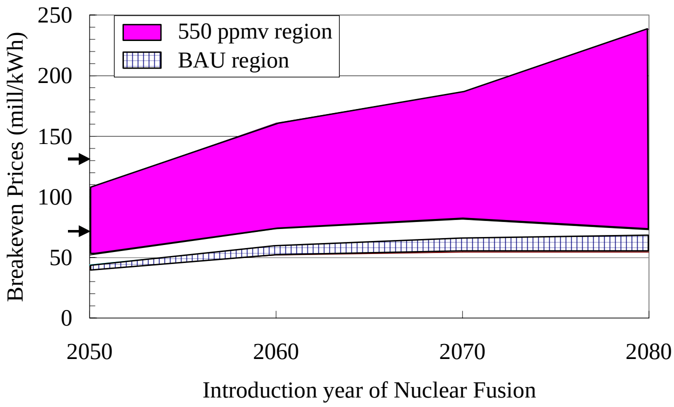

FIG 2. Coverage of possibility in economical introduction of tokamak-type nuclear fusion. The COE range of tokamak-type nuclear fusion reactors is around 70-130 mill/kWh as shown by allows. (source: ref.6)

Here, the vertical axis indicates how much the annual energy cost can be reduced till the end of the 21st century by introducing nuclear fusion. The "ideal (or unrealistic)" maximum potential of 350 Billion$/yr can be expected by introducing nuclear fusion in 2050. However, that is only the potential; the maximum 50 B$/yr and minimum 20 B$/yr reductions in the MCS case, and the maximum reduction, about 10 B$/yr and minimum some few Billions, correspond to the IIC case by introducing nuclear fusion in 2050. These values amount to only a few B$/yr at best by introducing nuclear fusion in 2060, and they become almost negligible by introducing beginning in 2070.

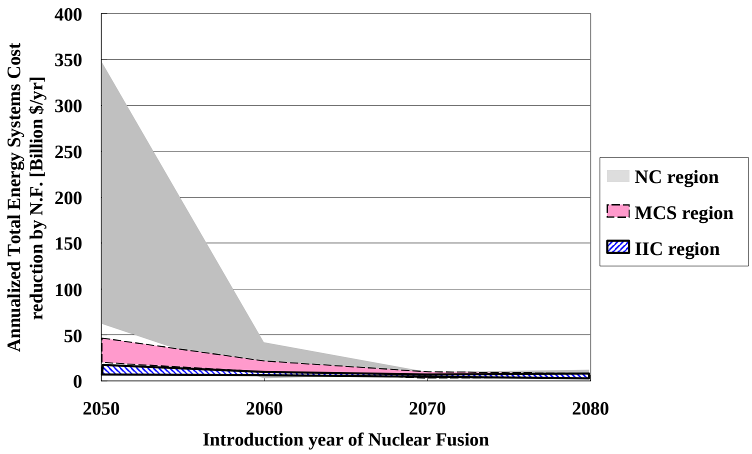

FIG 3. Summary of reductions in annualized total energy systems cost by nuclear fusion as a function of its introduction year in Billion $ per year. (source: ref.6)

Figure 4 indicates the carbon shadow price reduction by nuclear fusion in the same way as shown in Figure 3. The carbon shadow price corresponds to the ideal carbon tax under a CO_2 constraint that implies economic difficulty in CO_2 reduction. The vertical axis of Figure 4 exhibits percent reduction of carbon shadow prices from those without nuclear fusion. Introducing nuclear fusion reduces 10 % in the MCS case and 5 % in the IIC case when introducing in 2050, however it is declined to a few percentage or less in 2070 or 2080.

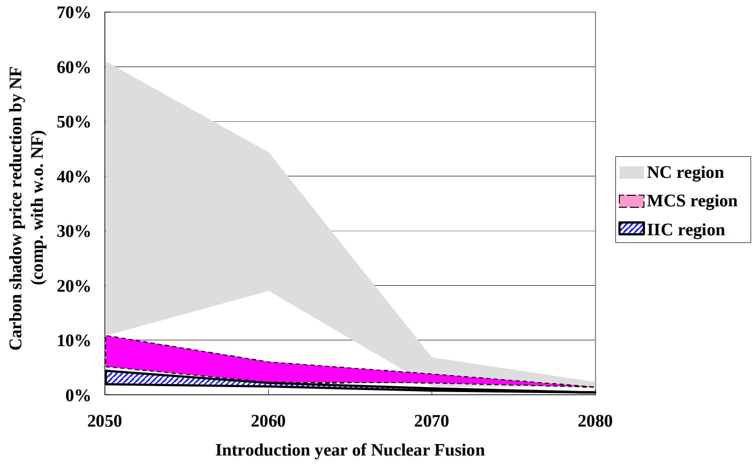

FIG 4. Summary of reductions in carbon shadow price by nuclear fusion as a function of its introduction year in $ per ton-C. (source: ref.6)

4. Conclusion

We conclude that the presently designed nuclear fusion reactors may be ready for economical introduction into energy systems beginning around 2050 - 2060, and we can confirm that earlier introduction (e.g., in 2050) of nuclear fusion of the reactors would reduce both the annual energy systems cost and the carbon tax (the shadow price of carbon) under a CO_2 concentration constraint; however, latter introduction of them decreases the cost and the tax less than five times. Earlier introduction of nuclear fusion reactors are desirable for energy systems and environment.

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