Introduction condition of a tokamak fusion power plant as an advanced technology in world energy scenario

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Abstract. The present study reveals the following two introduction conditions of a tokamak fusion power plant in a long term world energy scenario. The first condition is the electric breakeven condition, which is required for the fusion energy to be recognized as a suitable candidate of an alternative energy source in the long term world energy scenario. As for the plasma performance (normalized beta value β_N, confinement improvement factor for H-mode HH, the ratio of plasma density to Greenwald density limit fn_{GW}), the electric breakeven condition requires the simultaneous achievement of $1.2<\beta_N<2.7$, $0.8<HH$, and $0.3<fn_{GW}<1.1$ under the conditions of maximum magnetic field on TF coil B_{tmax}=16 T, thermal efficiency η_e=30%, and current drive power P_{NBI}<200MW. It should be noted that the relatively moderate conditions of $\beta_N\sim1.8$, HH~1.0, and $fn_{GW}\sim0.9$, which correspond to the ITER reference operation parameters, have a strong potential to achieve the electric breakeven condition. The second condition is the economic breakeven condition, which is required to be selected as an alternative energy source. By using a long term world energy and environment model, the potential of the fusion energy in the long term world energy scenario is being investigated. Under the constraint of 550 ppm CO_2 concentration in the atmosphere, a breakeven price for introduction of the fusion energy in the year 2050 is estimated from 65mill/kWh to 135mill/kWh, which is considered as the economic breakeven condition in the present study. Under the conditions of B_{tmax}=16T, η_e=40%, plant availability 60%, and a radial build with/without CS coil, the economic breakeven condition requires $\beta_N\sim2.5$ for 135mill/kWh of higher breakeven price case and $\beta_N\sim6.0$ for 65mill/kWh of lower breakeven price case. Finally, the demonstration of steady state operation with $\beta_N\sim3.0$ in the ITER project leads to the prospect to achieve the upper region of breakeven price in the world energy scenario.

1. Introduction

Fusion energy has been expected to be an innovative energy option, however, until now, it is not recognized as an alternative energy source even in a long term world energy scenario. This is because the fusion energy generates no available energy yet. On the other hands, burning plasma is supposed to be demonstrated in the ITER project in the near future. That means that the realization of the fusion energy will become feasible. For the smooth introduction of fusion energy as an energy source in the near future, the assessment of a practical roadmap for the fusion energy should be carried out. For example, the fast track concept aiming at early realization of fusion power plants suggested a roadmap somewhat different from the usual, i.e. the second and third stages in the case of the fast breeder reactor will be combined into a single step[1]. We have proposed a demonstration reactor in order to realize a commercial reactor with a single step following the ITER[2]. When such development scenario is constructed, it is inevitable that the introduction condition of the fusion energy as an alternative energy source has to be made clear. Recently, the potential of the fusion energy in a long term world energy scenario is being investigated, and the breakeven price of COE (cost of electricity) for the fusion energy is estimated[3]. In the present study, considering the introduction condition into the long term world energy scenario as the realization condition of the fusion energy, we investigate the plasma performance and reactor technology required to realize the fusion energy.

It is considered that there are three milestones toward the introduction of the fusion energy. The first one is the energy production equal to the input energy, which is the usual breakeven condition. The first milestone was completed, and we have to develop plasma performance and reactor technologies so as to generate net electric power in a plant scale, that is, the electric breakeven condition. This is the second milestone. The completion of the electric breakeven condition implies that the fusion energy is developed well enough to be one of the suitable candidates for the alternative energy source in the long term world energy scenario. The last one is to generate electric power economically enough to be selected as the alternative energy source, that is, the economic breakeven condition. The latter two conditions have to be completed in order that the fusion energy will be introduced into the long term world energy scenario. In the present paper, the electric and economic breakeven conditions as the introduction condition of the fusion energy into the world energy scenario are quantitatively investigated by using a fusion power plant system analysis code.

2. Long Term World Energy Scenario and Potential of Fusion Energy

The typical value of the economic breakeven condition is considered as the breakeven price for introduction of the fusion energy into the long term world energy scenario. Considering future uncertainties, e.g. energy demand scenarios and capacity utilization ratio of options in energy/environment technologies, Some of authors advance the analysis for the breakeven price of fusion energy by using a long term world energy and environmental model (this model is used for IPCC post SRES activity), and estimate that the breakeven price of the fusion energy for introduction in the year 2050 under the constraint of 550 ppm CO_2 concentration (twice level at the industrial revolution period) is the range of from 65 mill/kWh to 135 mill/kWh as shown in figure 1[4]. If the cost of electricity (COE) for the fusion energy can achieve the lowest breakeven price of this range, i.e. 65 mill/kWh in 2050, as a result of smooth introduction of the fusion energy, 20% share of the fusion energy in all produced electricity in 2100 is expected as shown in figure 2. This range of the breakeven price is estimated under the condition of the plant availability 60% for the first fusion power plant. This availability is rather low, because an unexpected outage of operation for the first fusion power plant should be considered in the plant availability. Of course, annual cost reduction of COE for 25 years after the first introduction is assumed because of improving the plant availability, operation cost and so on.

Figure 1 indicates that the later the introduction year of the fusion energy, the more expensive breakeven price is acceptable, however, it should be noticed that the share of produced

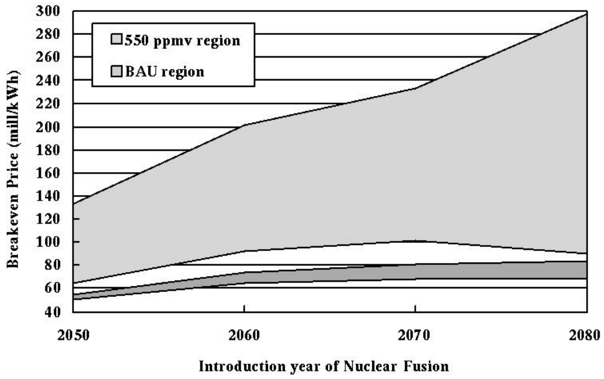

FIG. 1. Breakeven price as a function of nuclear fusion introduction year for 550 ppm of CO_2 constraint case and no CO_2 constraint case (business as usual, BAU case)

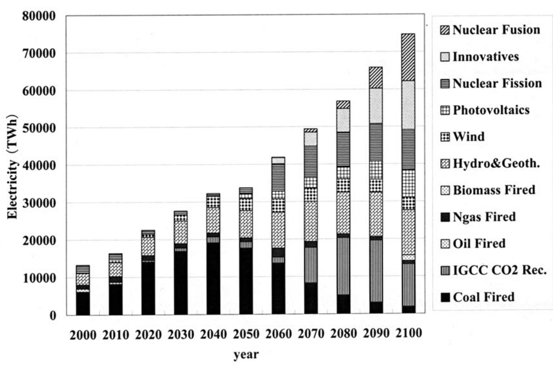

FIG. 2. Nuclear fusion's share of electricity assuming a 550 ppm CO_2 concentration constraint, a breakeven price of 65 mill/kWh for nuclear fusion.

electricity by the fusion energy in 2100 decreases with delay of the introduction year. For example, delayed introduction of the fusion energy in 2070 will result in only about 4% share in 2100. The earlier introduction of fusion energy, the more important role in the long term world energy scenario the fusion energy will play in 2100. The concentration of CO_2 in the atmosphere has been recognized as a critical environmental issue to date, and the CO_2 emission has to be decreased by the year 2050, so as to keep the CO_2 level at 550 ppm (less than the level of twice that at the industrial revolution period) by the year 2100[5]. Fusion energy has a potential enough to reduce the CO_2 emission[6], and when its introduction in 2050 is realized, consequently, the fusion energy can also contribute the world energy scenario to keep 550 ppm CO_2 level in 2100. The key point for maximizing the role of the fusion energy is how early fusion energy will be ready for electric power generation at a lower COE than the breakeven price. Delayed introduction at a lower cost is not effective for maximizing the role of the fusion energy. Hence, early demonstration of electric power generation in a plant scale is also important. In the present paper, we consider the introduction year 2050 of fusion energy as the year we should aim at, and we clarify the following conditions; (1) the electric breakeven condition which is required for the fusion energy to be recognized as a suitable candidate of an alternative energy source in the long term world energy scenario, and (2) the economic breakeven condition which is required to be selected as an alternative energy source.

3. Plasma Performance Required to Achieve the Electric Breakeven Condition

The electric and economic breakeven conditions of a tokamak fusion power plant are analyzed by using the Fusion power plant System Analysis Code (FUSAC)[7]. This system code is based on the CRIEPI cost assessment code (CCA code), which was used to clarify quantitatively that β_N is the most effective parameter to reduce the cost of electricity of a tokamak reactor[8]. The system analysis code FUSAC consists of three main parts. The first part is a zero-dimensional plasma analysis program based on the ITER physics design guidelines. The second is a simple engineering design program to determine the shape of the TF coil, the position and width for the components of the tokamak reactor (blankets, shields, and so on). The last part is an economic analysis program for the designed reactor based on the Generic Magnetic Fusion Reactor model (Generomak model). The detail of FUSAC is described in ref.[7].

In the present section, following engineering parameters are considered as the references; the thermal efficiency of electric conversion η_e=30%, the NBI system efficiency for the steady state operation η_{NBI}=50%, and the magnetic field on TF coils B_{tmax}=16 T. In the present paper, the maximum magnetic field of TF coils B_{tmax}=16 T with Nb_3Al and the NBI system efficiency η_{NBI}=50% are considered to be attainable in the near future in the basis of the ITER R&D program. The thermal efficiency of electric conversion is assumed to be almost the same as that of an usual light water reactor, because the coolant condition on the test breeding blanket proposed in the ITER program is similar to that of the usual light water reactor[9]. In addition, the following three conditions are considered. First, the current drive power P_{NBI} for the steady state operation is limited to 200 MW, because of the limit of available NBI ports and the necessity of a small circulating power. In the ITER NBI design, the injection power for a port is 16.5 MW[10]. If injection power of 33.0 MW, twice of the ITER design value, becomes possible, the total NBI power of 200 MW requires 6 ports, which is considered as the maximum port number in the present paper. Second, a sufficient space of 1.4 m for the blankets and the shields is maintained, because a tritium breeding ratio (TBR) larger than 1.0

has to be surely achieved. At last, the plasma current ramp-up is provided with the magnetic flux of CS coils.

With extensive analyses by using FUSAC, a database for about 100,000 operational points has been constructed under the conditions as mentioned in the previous paragraph. This database covers the conceivable plasma parameter ranges listed in TABLE I. With the database, investigation of the plasma performance required for net electric power generation was carried out. The main elements of the database are plasma performance parameters (normalized beta value β_N, confinement improvement factor for H-mode HH, a ratio of plasma density to Greenwald density limit fn_{GW}), plasma configuration parameters (major radius R_p, aspect ratio A, plasma elongation κ, plasma triangularity δ), other plasma parameters (temperature T_{ave}, plasma densities n_e and n_i, plasma current I_p, bootstrap current I_{bs} and so on), and engineering parameters (coil shape and its location, flux supply with CS coils Φ_{CS}, net electric power P_{enet}, circulating power P_{ecirc} and so on). The database also contains economic parameters, such as the cost of electricity and the construction cost. These elements are used in the following section.

TABLE I: PLASMA PARAMETER RANGES OF THE DATABASE FOR PLASMA OPERATION POINTS

Major radius R_p (m)	5.5-8.5
Aspect ratio, A	2.6-4.0
Plasma elongation, κ	1.8-2.0
Plasma triangularity, δ	0.35-0.45
Plasma temperature, T_{ave} (keV)	12-20
Plasma surface safety factor q_ψ	3.0-6.0

First of all, the requirements for a tokamak reactor to generate net electric power are investigated as for plasma performance parameters (β_N, HH, fn_{GW}). The plasma performance parameters required for net electric power P_{enet}=0, 400, 1000 MW are respectively plotted in figures 3. These results assumed κ=1.9 and δ=0.45. The electric breakeven (P_{enet}=0 MW) condition for normalized beta indicates the range of $1.2<\beta_N<2.7$ as shown in figure 3(a). The width of β_N plots for each net electric power results from a major radius mainly, that is, the plots for β_N=1.2 and β_N=2.7 in case of P_{enet}=0 MW correspond to R_p=8.5 m and R_p=6.0 m, respectively. For P_{enet}=1000 MW, β_N>3.0 is required. Regardless of net electric power, it should be noted in figure 3(b) that at least HH>0.8 is required for net electric power generation with the restriction of P_{NBI}<200 MW. The operational range of P_{enet}=1000 MW apparently shrinks in the region of HH>1.5 in comparison with that of P_{enet}=0, 400 MW, because the HH operating points of P_{enet}=1000 MW with HH>1.5, which have a large poloidal beta value and a small plasma current, results in a larger bootstrap current than the total plasma current. Therefore, such operating points with a large bootstrap current fraction beyond unity are excluded in the present paper. A large fn_{GW} is required as P_{enet} becomes large as shown in figure 3(c), and this tendency is also similar to that of β_N. The electric breakeven condition is provided with the fraction of Greenwald density limit of $0.3<fn_{GW}<1.1$. When P_{enet}=1000 MW is aimed at, at least fn_{GW}>0.9 is required.

Figure 4 describes the attainable region of net electric power with several plasma performances of β_N, HH, and fn_{GW}, on Q vs. P_f (energy multiplication factor and fusion power) space for each major radius of R_p=8.5, 7.5, and 6.5 m. Each figure consists of two plots. The first one is the plot for net electric power P_{enet} on Q vs. P_f. The other is for plasma performance parameters on Q vs. P_f. The former relationship is evident for given engineering parameters. The latter one is derived in the previous paragraph. Simply speaking, figures 4 are

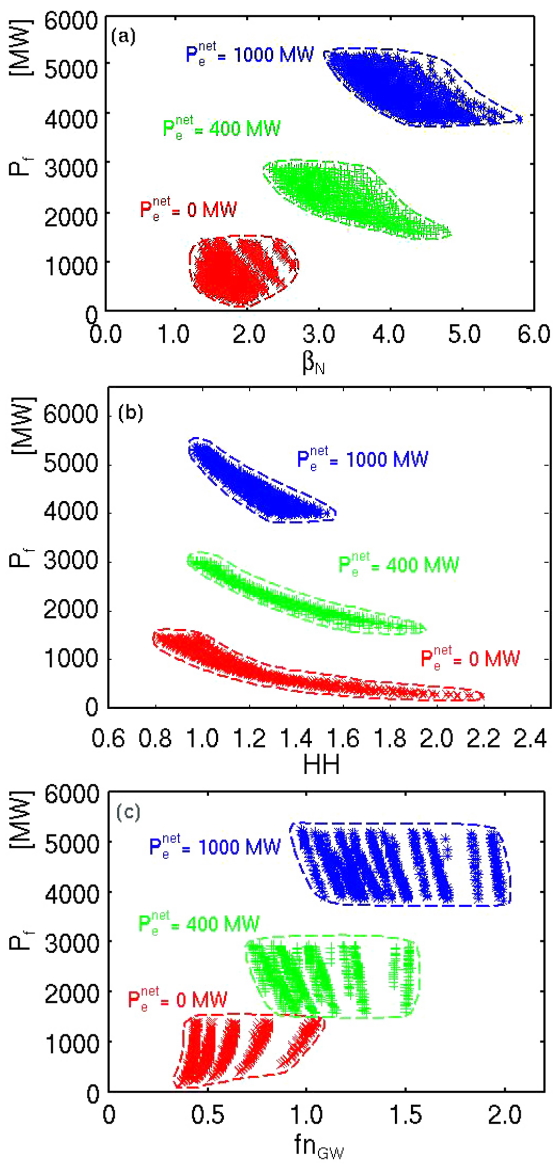

FIG. 3. Plasma performance required for each net electric power P_{enet}. (a) required β_N, (b) required HH, and (c) required fn_{GW}.

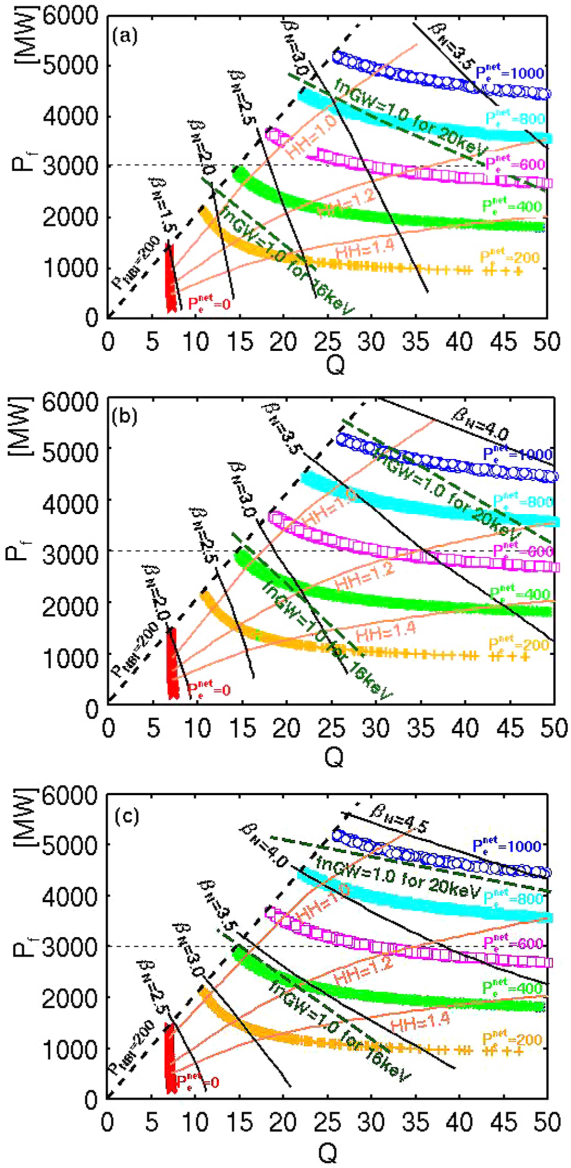

FIG. 4. Plasma performance diagram on Q vs.P_f space for (a) R_p=8.5 m, (b) R_p=7.5 m, and (c)R_p=6.5 m. Each net electric power P_{enet} are also ploted.

the superpositions of above two plots. With these figures, brief estimation of the plasma performance required for a tokamak reactor to generate net electric power can be made. The plasma performance lines for β_N, HH, and fn_{GW} in figures 4 delineate the attainable boundaries of respective plasma performance. For example, fn_{GW}>1.0 is always needed for the domain above the line of fn_{GW}=1.0, whereas for the domain below the line it is not. It should be noted that the domain below the line of fn_{GW}=1.0, where all the operational points of fn_{GW}<1.0 are contained, includes also operational points with fn_{GW}>1.0. Similarly, the other plasma parameter lines shown in figures 4 delineate respective attainable boundaries. In these figures, the operational points for each net electric power only with P_{NBI}<200 MW are plotted.

The attainable region with R_p=8.5 m is depicted in figure 4(a). This figure shows that a moderate normalized beta value of β_N~1.5 has a potential to achieve P_{enet}=0 MW with HH~1.0 and fn_{GW}<1.0. When P_{enet}=600 MW, which corresponds to P_f~3000 MW with η_e=30 %, are aimed at with R_p=8.5 m, the required β_N becomes about β_N~3.0. In figures 4, the two attainable boundaries of fn_{GW} are delineated for plasma temperatures of T_{ave}=16 keV and

T_{ave}=20 keV. In case of R_p=8.5 m, the condition of Greenwald density limit is more severe than in case of smaller major radius. Specifically, an electric power larger than P_{enet}=200 MW cannot be attained with fn_{GW}<1.0 under the condition of T_{ave}<16 keV. Figure 4(b) shows that the requirement for β_N to achieve P_{enet}~ 0 MW with R_p=7.5 m becomes a little demanding, i.e. β_N~2.0. This result implies that the progress of ITER program as planned at present will enable achieving electric breakeven condition P_{enet}=0 MW with a major radius R_p=7.5 m. In additions, it is possible to attain P_{enet}~600 MW with P_f~3000 MW with β_N<3.5 which is considered to be the ideal MHD beta limit. This plasma performance of β_N~3.5 may be examined with ITER[11]. In case of R_p=6.5 m in figure 4(c), the β_N requirement for P_{enet}=0 MW with R_p=6.5 m is about β_N~2.5, which is considered to be feasible in the ITER project, but it is larger than that of ITER reference parameter. When P_f~3000 MW is aimed at with R_p=6.5 m, it is necessary to attain β_N>3.5 which may require some stabilizing effects, e.g. by using a conducting wall in the blanket. However, if it is possible, its construction cost is considered to be moderate and the perspective for demonstrating economic performance is relatively easy to obtain.

The comparison of figures 4 indicates that β_N depends on the major radius R_p. This dependence of R_p on the required β_N corresponds to the width of operational plots for β_N in figure 3(a). On the other hand, the attainable boundary of HH is almost parallel to the restriction of P_{NBI}, which means that the restriction of P_{NBI} has a great impact on HH. Moreover, figures 4 reveal that improvement in HH at a constant β_N cannot always increase the net electric power. It is also found in figures 4 that the fn_{GW} requirement depends on the plasma temperature. P_f>3000 MW cannot be attained with fn_{GW}<1.0 under the condition of T_{ave}<16 keV.

4. Plasma Performance Required to Achieve the Economic Breakeven Condition

The database constructed by FUSAC is also applied to this parametric analysis to clarify the plasma performance required to achieve the breakeven price of from 65 mill/kWh to 135 mill/kWh in the year 2050. The result of the economic breakeven condition for a tokamak fusion power plant with B_{tmax}=16 T, P_{enet}=1000 MW and plant availability 60% is shown in figure 5. Each operational space in figure 5 is composed of the plots for possible operation points. Those operational points are calculated under the same conditions as in the previous section except: (1) thermal efficiency η_e=40%; (2) the feasibleness of a simplified radial build without CS coils (which means full non-inductive current ramp up is required in case of without CS coils). In the present study, when there is not space sufficient enough to locate the CS coils with the same B_{tmax} and coil current density J_{tfc} as TF coil, that radial build is designed without CS coils. Note that β_N more than 2.5 has a potential to achieve the upper region of the breakeven price in the long term world energy scenario. This β_N value is supposed to be attainable by the ITER advanced plasma performance aiming at the steady state operation[10], which implies that the completion of ITER advanced plasma with β_N~3.0 lead to the possibility of introduction of the fusion energy in the world energy

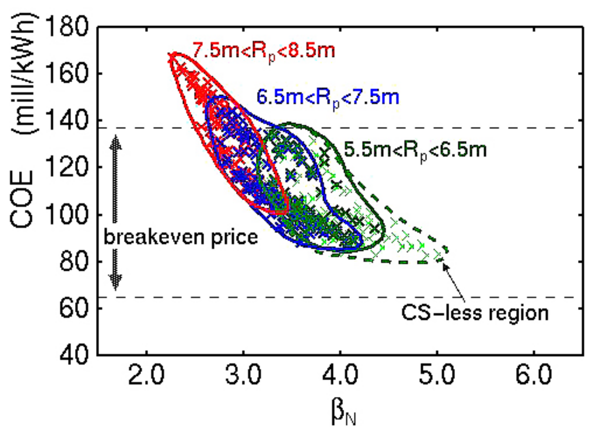

FIG 5. Normalized beta value β_N vs. Cost of Electricity (COE) for 16T with the breakeven price of fusion energy. The broken line shows the extension without CS coils(CS-less).

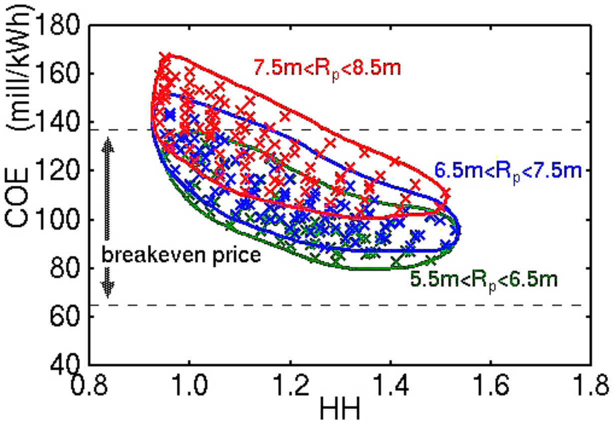

FIG 6. Confinement improvement factor HH vs. Cost of Electricity (COE) for 16T with the break-even price of fusion energy.

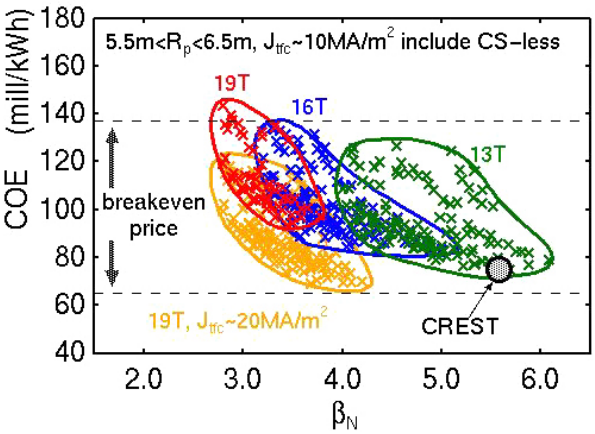

FIG 7. Dependence of B_{tmax} on COE for 5.5 m<R_p<6.5 and J_{tfc}~10MA/m^2 of TF and CS coils. The COE region for 19T with J_{tfc}~20MA/m^2 is also shown. The CREST design point is located in the lower limit of the 13 T case.

scenario. On the other hand, to achieve the most severe case of the breakeven price 65mill/kWh, β_N>5.0 with smaller major radius R<6.0 m is required. As shown in figure 5, the simplified radial build without CS coil (CS-less region) is required to attain the lower boundary of COE with 5.5 m<R_p<6.5 m. This is because the current density of TF and CS coils is not large enough to make a sufficient space for CS coil in the central torus region. In this result, overall current density of TF coil is J_{tfc}~10MA/m^2, which is almost the same as the ITER design[10].

Figure 6 shows the HH region required to achieve the breakeven price. The higher HH is the lower COE is because of reducing the cost for the current drive system, however, in contrast with β_N, the required HH region is almost the same through the range of 5.5 m < R_p < 8.5 m. The most important suggestion in this figure is that there is no path with HH<0.9 to introduction of the tokamak fusion reactor into the long term world energy scenario. The fn_{GW} required to achieve the breakeven price (which is not shown in a figure) has no clear dependence on COE. This is mainly because both the required density and the density limit are decreased as the major radius increases under the condition of the almost the same P_f.

Figure 7 shows the dependence of B_{tmax} on COE in case of 5.5 m<R_p<6.5 m. These data reveal that the increase of B_{tmax} is very effective for the decrease of the required β_N under the condition of including a CS-less radial build. On the other hand, the increase of B_{tmax} increases the lowest limit of COE under the condition of the same critical current density. This comes from the increase of the coil volume or the device size, and the lower limit of COE range of 19 T increases up to 90mill/kWh. To get the merit of high magnetic field, the current density of super conductor also has to be improved. When current density about 20MA/m^2 of TF coils is feasible with the same cost as a 10MA/m^2 coil, the merit of high magnetic field is clearly obtained, that is, the decrease of required β_N with the same COE as 13T is possible as shown in figure 7. For example, use of a high temperature super conductor with low temperature is effective to increase the current density of TF coils. When the advanced plasma with β_N~6.0 is possible, a super conductor of 13 T is almost sufficient enough to achieve the lower region of breakeven price of 65mill/kWh. The design for a commercial plant CREST[12], where R_p=5.4 m, η_e=41%, B_{tmax}=13T, is near the breakeven price of 65mill/kWh.

5. Summary

A condition for introduction of a tokamak fusion power plant into the world energy scenario is analyzed. We consider the introduction year 2050 of the fusion energy as the year we should aim at, and we clarify the following conditions; (1) the electric breakeven condition which is required for the fusion energy to be recognized as a suitable candidate of an alternative energy source in the world energy scenario, and (2) the economic breakeven condition which is required to be selected as an alternative energy source. The electric breakeven condition requires the simultaneous achievement of $1.2<\beta_N<2.7$, $0.8<HH$, and $0.3<fn_{GW}<1.1$ under the condition of B_{tmax}=16 T, η_e=30%, and $P_{NBI}<200$MW. It should be noted that the relatively moderate conditions of β_N~1.8, HH~1.0, and fn_{GW}~0.9, which correspond to the ITER reference operation parameters, have a strong potential to achieve the electric breakeven condition. The economic breakeven condition requires β_N~2.5 for 135mill/kWh of higher breakeven price case and β_N~5.0 for 65mill/kWh of lower breakeven price case under the conditions of B_{tmax}=16T, η_e=40%, plant availability 60%, and feasibleness of a simplified radial build without CS coil. The demonstration of steady state operation with β_N~3.0 in the ITER project leads to the prospect to achieve the upper region of breakeven price in the world energy scenario. This β_N requirement will be somewhat mitigated with higher B_{tmax},, however, current density of TF and CS coils has to be simultaneously improved to obtain the clear merit of higher magnetic field.

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