Economic and Environmental Assessment Modeling of Magnetic and Inertial Fusion Reactors

Kozo YAMAZAKI, Satoshi UEMURA*, Tetsutarou OISHI

Nagoya University, Chikusa-ku, Nagoya 464-8603 Japan

**present address: Chugoku Electric Power Co. Inc, Matsue, Shimane 690-0393 Japan*

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In order to search for economically and environmentally optimized fusion reactors, physics properties, engineering designs and the cost of electricity (COE) are evaluated by the PEC (Physics-Engineering-Cost) system code for several magnetic confinement fusion reactors including tokamak (TR), helical (HR) and spherical tokamak (ST) reactors. The life-cycle CO_2 emission amounts are also evaluated for various blanket designs using input-output table. This code has recently been upgraded to apply to inertial fusion reactor (IR) designs. The advantage of high-beta TR designs in COE and the advantage of compact ST designs in life-cycle CO_2 emission reduction are clarified in the present economical and environmental assessments. The probable merits of IR design in both values are also clarified in the present model. The increase in net electric fusion power from 1GW to 3GW leads to 38% reduction in COE and 23% reduction in CO_2 emission amounts. The scaling formulas of COE and CO_2 emissions are derived as a function of plasma beta and net electric power. When the carbon tax of around 3,000 yen/t-CO_2 is introduced, the COE of fusion reactor might be same level on that of coal-fired electric power plant and 1.5 times lower than that of oil-fired electric power plant.

Keywords: cost of electricity, CO_2 emission, tokamak reactor, helical reactor, inertial fusion reactor, tritium breeding blanket

1. Introduction

Global warming due to rapid CO_2 emission is one of the present-day crucial problems all over the world, and nuclear power plant systems including future fusion reactors are expected as an abundant electric power generation system to reduce global warming gas emission amounts.

In order to search for economically and environmentally optimized reactor designs, the system analysis of fusion reactors on physics, engineering, cost and CO_2 emission amounts has been carried out for toroidal magnetic confinement fusion (MCF) reactor designs, and some comparative studies among conventional electric power generation systems were carried out [1-3]. Here, we extend this to the inertial confinement fusion (ICF) system, and include the effect of CO_2 tax. Various blanket designs including fission-fusion (F-F) hybrid and D-^{3}He reactor designs are assessed with respect to the cost of electricity (COE) and the life-cycle CO_2 emission amounts.

2. System code description

We compared several fusion reactors from the view point of the scale of reactor, the cost of electricity (COE) and the life-cycle CO_2 emission amounts. Magnetic confinement systems evaluated here are Tokamak Reactor (TR), Helical Reactor (HR) and Spherical Tokamak reactor (ST). These models are calculated by the system design code Physics-Engineering-Cost (PEC) [1-3].

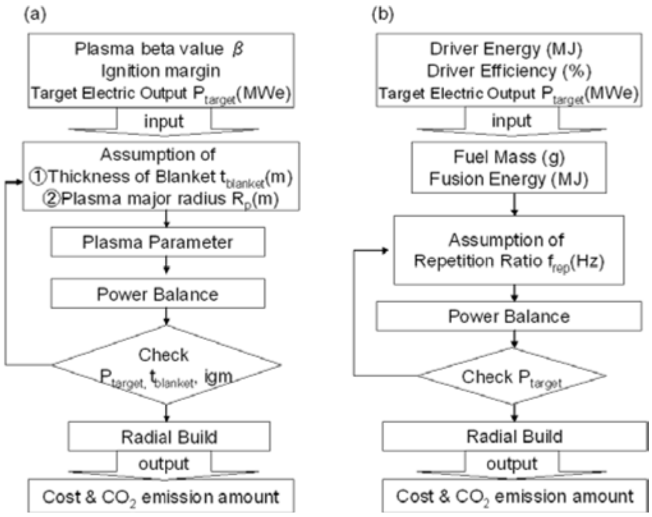

Fig 1 Assessment flow chart of (a) magnetic confinement fusion and (b) inertial confinement fusion reactor designs

The flow chart is shown in Fig.1(a) for magnetic confinement fusion (MCF) system. The main input parameters are the net target electric power P_{target}, ignition margin and plasma beta value. The flow chart of

author's e-mail: yamazakl@ees.nagoya-u.ac.jp inertial confinement fusion (ICF) reactor design is shown in Fig.1(b). In this model the driver energy E_{driver} and driver efficiency determine the main components of this ICF system.

2.1 Physics Models

(1) Magnetic Fusion Reactors

Reactor plasma performances are determined by plasma beta, plasma confinement and density limit scaling laws. We adopted several confinement scaling laws. As for tokamak models the ITER Elmy H-mode confinement scaling [4] with improvement factor is used. The alpha- particle confinement fraction is assumed to be 0.95 for standard tokamak and spherical tokamak reactors and 0.9 for helical reactors. The normalized beta value is 4.0 for the reference tokamak design and 6.0 for the reference spherical tokamak design. For steady-state helical system the averaged beta value of 5% is assumed with confinement improvement from international stellarator confinement scaling laws. The density limit of the helical system (two times larger than old LHD density scaling law) is also considered [3] in comparisons with Greenwald tokamak density limit.

These plasma scaling laws and databases for both systems are checked comparatively. In addition to simplified zero-dimensional power balance model with profile corrections, the 1.5- or 2.0- dimensional equilibrium-transport predictive simulation code TOTAL [1] with empirical local transport coefficients has been carried out for the physics projections to the TR, HR and ST designs, which justified the present simplified zero-dimensional analysis. Figure 2 shows these three-types of reactor concepts.

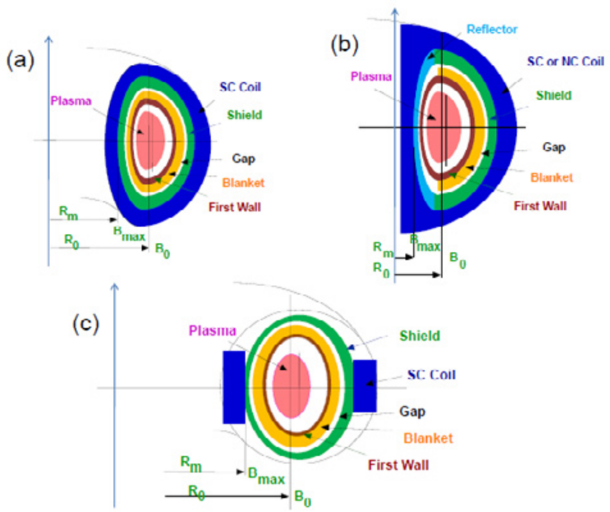

Fig. 2 Models of (a) tokamak (TR), (b) spherical tokamak (ST) and (c) helical reactor (HR) designs

(2) Inertial Fusion Reactor

For ICF reactor designs, fast ignition concept is adopted here. Mass of fuel M_{fuel} which would be compressed and heated is estimated by given driver energy E_{driver} and driver efficiency η_{driver} as follows.

$$E_{driver} = \frac{E_c}{\eta_c} + \frac{E_h}{\eta_h} \qquad (1)$$

$$E_c = 0.324\rho_c^{2/3}\alpha M_{fuel} ,$$

$$E_h = 115T_h(\frac{0.5}{\rho_c R})^3 M_{fuel}$$

$$M_{fuel} = \frac{4\pi}{3}\frac{(\rho_c R)^3}{\rho_c^2},$$

where R, ρ_C, α and T_h are plasma radius, compressed density, isentrope parameter (~3) and hot plasma temperature (~10keV), respectively. The compression and heating efficiencies are η_c(~0.05) and η_h(~0.1). Fusion energy E_{fus} is calculated by the fuel mass M_{fuel} and burn-up fraction Φ,

$$E_{fus} = \frac{17.6}{2}\Phi\frac{M_{fuel}}{m_{DT}} , \qquad (2)$$

and the repetition rate f_{rep} is adjusted to satisfy the following power balance,

$$P_{net} = f_{elect}P_{th}(1 - f_{plant}) - \frac{E_{driver} \times f_{rep}}{\eta_{driver}}, \qquad (3)$$

Figure 3 shows pellet gain curves calculated by the present simplified model [5, 6]. Typical design values of various conceptual reactor designs are also plotted.

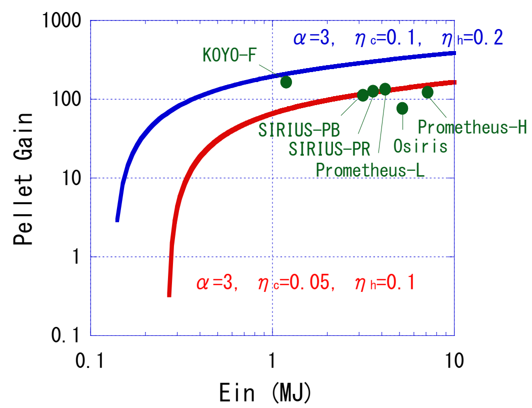

Fig.3 Pellet gain curves as a function of driver energy for ICF reactors. Various conceptual reactor design values are plotted comparing with the present model curves.

2.2 Engineering Models

(1) Magnetic Fusion Reactors

As for engineering design of tokamak and helical reactors, the power flow is shown in Fig.4. In the tokamak reactors, the required current drive (CD) power P_{CD} might significantly contribute to the circulating power flow. The thermal efficiency η_e and CD power supply efficiency η_{CD} are also included in the power flow chart.

The blanket thickness and the relevant gaps are critical parameters to determine the reactor radial build. Here, we assume the following scaling law of total blanket thickness as a function of neutron wall loading L_{wall} based on various conceptual design works;

$$t_{total}[\mathrm{m}] = 0.10 \times L_{wall}[\mathrm{MW/m^2}] + 0.8$$

for liquid breeder blanket (Li/V, Flibe/FS, LiPb/SiC), and

$$t_{total}[\mathrm{m}] = 0.15 \times L_{wall}[\mathrm{MW/m^2}] + 0.8$$

for solid breeder blanket (Li_2O/SiC). The thickness of F-F hybrid blanket is assumed 1.5 times as large as that of Flibe/FS blanket. The ratios of blanket thickness to total thickness are 0.3, 0.45, 0.70, 0.40 and 0.7 for Li/V, Flibe/FS, LiPb/SiC, Li_2O/SiC, and F-F hybrid, respectively. The thermal efficiencies of Li/V, Flibe/FS, LiPb/SiC, Li_2O/SiC and F-F hybrid are assumed as 46%, 40%, 50%, 49% and 40 %, respectively. All these assumed data are based on various conceptual designs

The reference magnet system is assumed made of Nb_3Sn conductor, and its maximum magnetic field strength is assumed 13 Tesla.

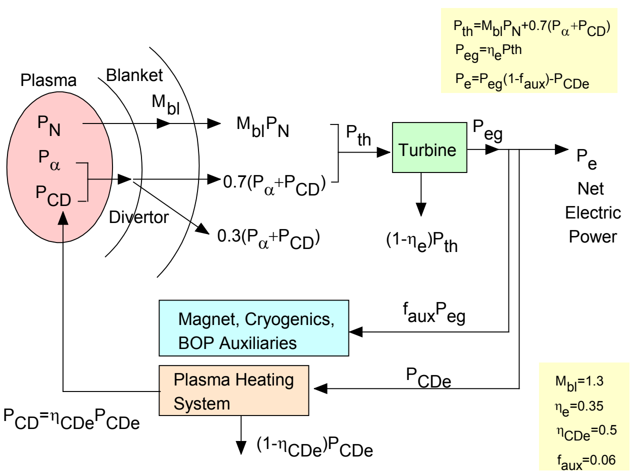

Fig.4 Power flow of MCF reactor

The superconducting magnet engineering scaling law is described in Ref. [7]. The coil current density, coil stress, wall loading and other engineering items are evaluated. These assumptions and relevant physics/engineering models determine the plasma-coil space and the scale of the reactor system.

Table 1 shows main parameters of reference magnetic confinement fusion reactors obtained by the PEC code with the same electric output (1000 MWe) assumed.

(2) Inertial Fusion Reactors

The radius of ICF cylindrical chamber R_{fw} should be determined by the detailed design analysis and might be a function of the neutron wall load or fusion energy E_{fus}. Here we assumed the following scaling laws derived based on previous ICF conceptual design works:

$$R_{fw}[\mathrm{m}] = (E_{fusion}[\mathrm{MJ}] + 1000)/300$$

The obtained main parameters of reference inertial confinement fusion reactor are shown in Table 2.

Table1 Reference magnetic confinement fusion reactors with electric output (1000 MWe), operation year (30 years) and plant availability (0.75).

Reference Reactor	TR		ST	HR
confinement scaling*	ITER Elmy H mode			ISS
Fuel*	D-T	D-^{3}He	D-T	D-T
normalized β-value	4	6	6	-
average β-value (%)*	-	-	-	4
Aspect ratio	3.5	3.5	1.6	7.8
Average temperature (keV)*	15	42.5	15	10
Major radius (m)	6.3	13.9	4.3	14.9
Toroidal field (T)	6.2	8.4	2.5	4.7
Fusion power (GW)	3.48	4.82	4.19	2.35
Average density (10^{20}/m^3)	1.5	1.5	1.0	1.0

* input parameter

Table2 Reference inertial confinement fusion reactor with Li breeder liquid wall.

Net electric power P_{enet} (MW)*	1000
Driver energy E_{driver} (MJ)*	3.4
Driver efficiency η_{driver}*	0.075
Pellet gain G_{pel}	120
Mass of fuel M_{fuel} (mg)	4.5
Repetition rate f_{rep} (Hz)	6.5
Chamber size R_{fw} (m)	4.4
Total fusion power P_{fus} (GW)	2.64

* input parameter

2.3 Cost Accounting Model

(1) MCF designs

The cost analysis is mainly based on the unit costs per weight which values are mainly based on those of Refs. [8-10]. The unit cost of helical coil is assumed 25% higher than those of toroidal and poloidal coils. The cost of superconducting toroidal coil with weight W_{TFC} is assumed as $0.114 \times W_{TFC}(\mathrm{t})[\mathrm{M\$}]$. The other main detailed values used here are shown in Ref.[3].

(2) ICF designs

Relevant to ICF designs, costs of plant systems except driver system and pellet fabrication are calculated by the same scaling data in the PEC code for MCF models. Here, driver system cost ($163E_{driver}(\mathrm{MJ}) + 113$ [M$]) and pellet fabrication cost ($132(\frac{f_{rep}(\mathrm{Hz})}{5.6})^{0.7}+66$ [M$]) are given by the scaling law described in Ref. [5].

2.4 CO_2 emission Models

(1) MCF designs

To estimate life-cycle CO_2 emission amounts, we used basic unit for CO_2 weight (k-t-CO_2/t-material) based on input-output table [3,11,12]. CO_2 emissions from mining, transport and fabrication of various components are totally included in this table.

(2) ICF designs

For IR designs CO_2 gas is emitted mainly at the driver system construction stage. The chamber size and the pellet fabrication system determined by the driver repetition rate are also strongly related to CO_2 emission amount. The calculation procedure for ICF is almost same as that of MCF reactors.

3. Assessment Results

3.1. Beta dependence for tokamak reactors with different blanket designs

The reactor scale is determined by the radial build and the thickness of the blanket and shield is strongly related to this radial build in MCF designs. Figure 5 shows the assessment results of tokamak reactors with different blanket systems as a function of normalized beta value.

The liquid breeder LiPb/SiC design is rather compact because of high thermal efficiency and small thickness assumed. The most compact design is F-F design including UO_2 ($\beta_N=4$, assumed neutron multiplication factor is 6.0) with thick blanket assumed 1.5 times as thick as that of liquid breeder blanket.

The low COE design is expected by the Li/V blanket, but is disadvantageous in CO_2 emission due to high CO_2 emission unit assumed from Vanadium. The lower CO_2 emission is realized by LiPb/SiC or LiO_2/SiC blanket designs.

In spite of difference of various blanket designs we obtain the following scaling formulas for plasma major radius R_p, COE and unit CO_2 emission of Tokamak Reactor (RT) within the range of : $\beta_N \sim 3-6$;

$$R_P(RT) \propto \beta_N^{-0.48\pm0.02},$$

$$COE(RT) \propto \beta_N^{-0.59\pm0.05},$$

and

$$CO_2(RT) \propto \beta_N^{-0.29\pm0.03}.$$

The beta dependence of CO_2 emission is slightly weak than that of COE.

3.2. Driver energy dependence for inertial fusion reactors

Figure 6 shows the assessment result of ICF design. The driver electric power efficiency of 7.5% is assumed and the repetition rate of driver is calculated. When the driver energy is low, the repetition rate should be high. If the driver energy becomes higher, the larger chamber and thicker blanket might be required. Therefore there is an

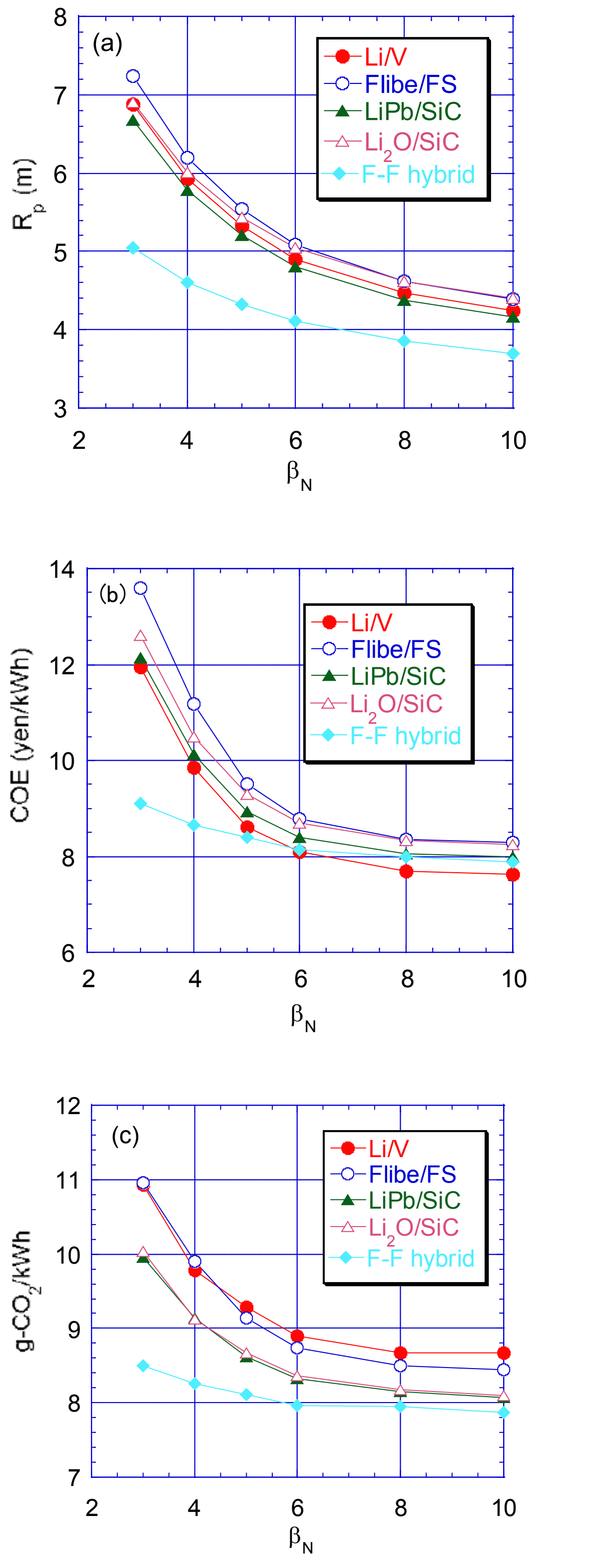

Fig.5 Normalized beta dependence of (a) major radius, (b) COE and (c) CO_2 emission amounts for tokamak reactor.

optimal design point for driver energy ($E_{driver} \approx 3MJ$). Here the blanket exchange rate is assumed 2 times lower than that of MCF designs, and the COE and CO_2 emission is found to be lower than those of MCF models.

3.3. Assessment of higher power plant

In addition to increasing beta value, the lower COE can be realized by increasing maximum magnetic field (reference design: 13 T for superconducting TR, and 8T for normal conducting ST), operation period (reference design: 30 years) and net electric power output (reference design: 1GW-electric).

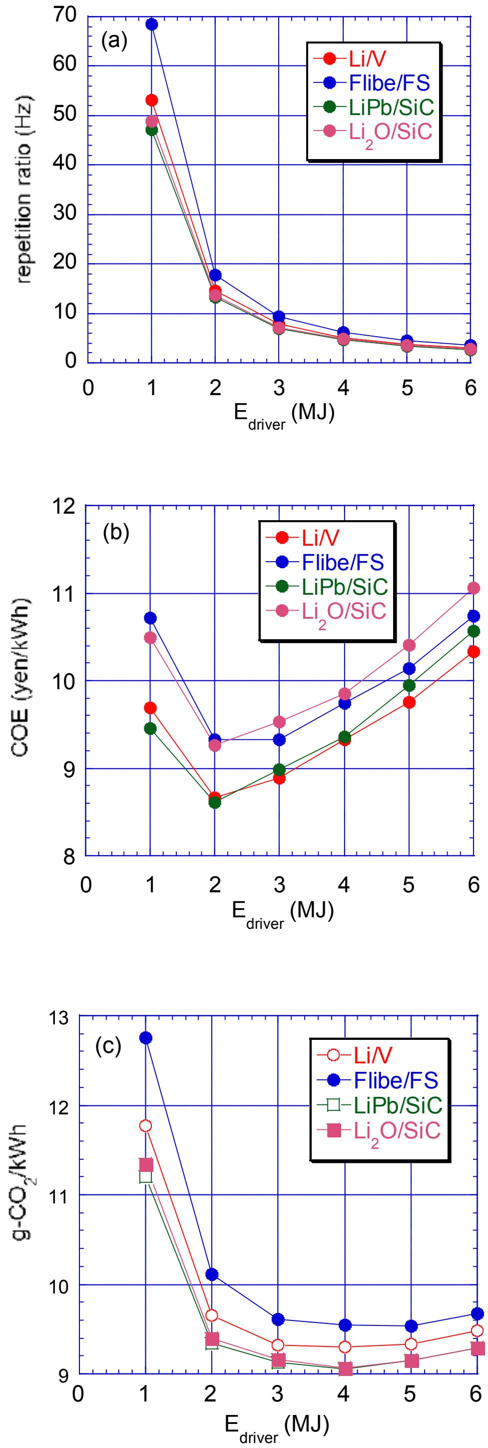

Fig.6 Driver energy E_{driver} dependence of (a) repetition rate, (b) COE and (c) CO_2 emissions for ICF reactors.

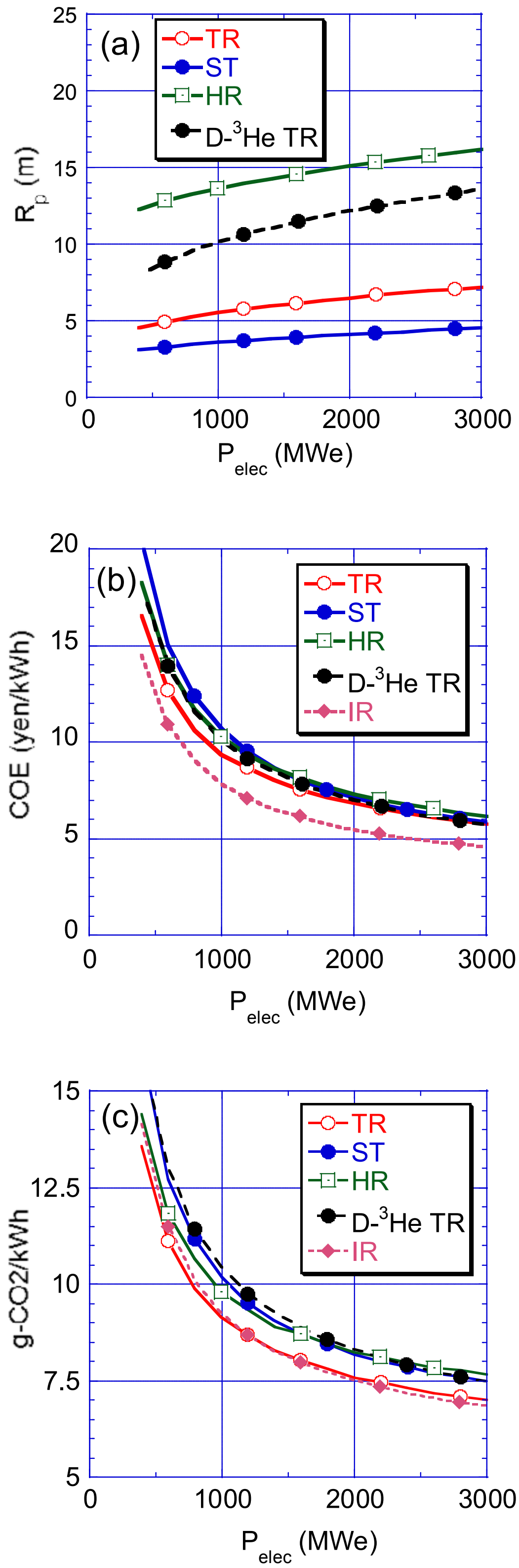

Fig.7 Electric power P_{elec} dependence of (a) plasma major radius, (b) COE and (c) CO_2 emission amounts.

Figure 7 show the effect of net electric fusion power increase on COE and CO_2 emission. The assumed normalized beta values are 4.0 (TR), 6.0 (ST) and 6.0 (D-^{3}He fuel TR). The averaged beta of HR is assumed 4.0%. The major radius of TR should be increased from 5.5m to 7.2m to raise net electric power from 1GW to 3 GW. In this case COE and CO_2 unit emission are reduced from 9.4 yen/kWh and 9.1 g-CO_2/kWh to 5.8 yen/kWh and 7.0 g-CO_2/kWh, respectively. The power dependence of COE and CO_2 emission value of HR is almost same as those of TR, and scaling formulas as $COE \propto P_{elec}^{-0.51\pm0.01}$ and $CO_2 \propto P_{elec}^{-0.30\pm0.01}$ are obtained. These are slightly different from those of D-^{3}He design (small thickness blanket) and ST design (Normal conductor and no inner blanket) with $COE \propto P_{elec}^{-0.58\pm0.02}$ and $CO_2 \propto P_{elec}^{-0.36}$. Therefore, HR curve crosses the D-^{3}He and ST curves in this assessment. Despite of the difference of reactor designs, the COE reduction is larger than the CO_2 unit emission reduction when the net electric power is increased.

3.4. Comparisons with Other Electric Power Generation Systems

By comparing fusion reactors with other electric power generation systems [13] from the view point of COE and CO_2 emission amount, we confirmed that fusion reactor emits less CO_2 amount. Therefore, there is little influence of introducing carbon tax on economics of fusion reactors, and COE of fusion reactor might be lower than that of oil-fired electric power plant when around 3,000 yen/t-CO_2 carbon tax (Sweden's present carbon tax is 3,800 yen/t-CO_2) is introduced.

4. Summary

In order to find out scaling formulas of cost of electricity and CO_2 emissions on key reactor parameters, and to search for economically and environmentally optimized fusion reactors, system analyses of typical 1GW-electric fusion reactors, such as tokamak (TR), spherical tokamak (ST) and helical (HR) reactors, were carried out using PEC (Physics-Engineering-Cost) system code. Inertial confinement fusion Reactor (IR) is also evaluated by upgrading this code assuming its driver energy and driver efficiency. In addition, different blanket modules including fission-fusion hybrid and D-^{3}He fuels are considered in these designs.

The advantage of high-beta tokamak reactors in COE and the advantage of compact spherical tokamak in lifetime CO_2 emission reduction are clarified in the present economical and environmental assessments. The COE and CO_2 emission dependences on plasma beta value are obtained, and the CO_2 emission is clarified to depend weakly on beta. The possible advantage of inertial fusion reactors in both values is also clarified in the present model. The electric power dependences of COE and CO_2 emissions are also clarified.

By comparing fusion reactors with other electric power generation systems from the view point of COE and CO_2 emission amount, we confirmed that COE of fusion reactors is two times higher than that of coal-fired electric plant and that of atomic power plant. On the other hand, the life-cycle CO_2 emission amount from fusion reactor is slightly less than that of atomic power plant.

When the carbon tax of around 3,000 yen/t-CO_2 is introduced, the COE of fusion reactor might be same level on that of coal-fired electric power plant and 1.5 times lower than that of oil-fired electric power plant.

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