Environmental and Economic Assessments of Magnetic and Inertial Confinement Fusion Reactors

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Abstract. Global warming due to rapid greenhouse gas (GHG) emissions is one of the present-day crucial problems, and fusion reactors are expected as abundant electric power generation systems to reduce human GHG emission amounts. To search for an environment-friendly and economical fusion reactor system, comparative system studies have been done for several magnetic fusion energy (MFE) reactors, and been extended to include inertial fusion energy (IFE) reactor. We clarify new scaling formulas for cost of electricity (COE) and GHG emission rate with respect to key design parameters, which might be helpful for making a strategy of fusion research development. The comparisons with other conventional electric power generation systems are carried out taking care of the introduction of the GHG taxes and the application of the CCS (carbon dioxide capture and storage) system to fossil power generators.

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 fusion reactors are expected as an abundant electric power generation system to reduce global greenhouse gas (GHG) emission amounts.

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

2. Assessment Models

The physics, engineering designs and the economics are evaluated by the PEC (Physics-Engineering-Cost) system code [1,2] for MFE reactors, including tokamak reactor (TR),

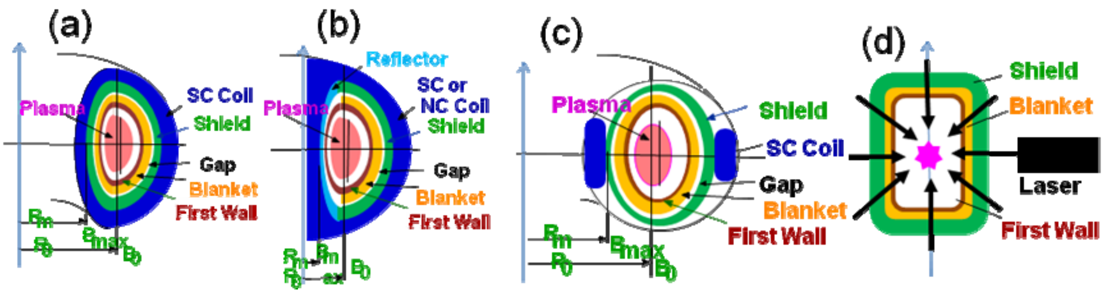

FIG. 1 Schematic drawing of reactor core models; (a)tokamak reactor (TR), (b)sphelical tokamak reactor (ST), (c) helical reactor(HR), and (d) inertical confinement reactor (IR)

helical reactor (HR) and spherical tokamak reactor (ST), and for IFE reactor (IR) schematically shown in Fig.1. These MFE reactor designs strongly depend on the radial build determined by the achievable plasma beta value and magnetic field strength. On the otherhand, IR designs depend on the driver energy and its repition rate.

2.1. Physics and Engineering Models

(1) Magnetic Fusion Reactor

Figure 2 shows flow charts of PEC system code. For MFE reactor assessment, target electric power output, ignition margin, plasma beta value and so on, are used as input parameters. As for tokamak and helical confinement models, ITER Elmy H-mode [4] and international stellarator scaling (ISS) laws [5] with improvement factor are checked, respectively. The alpha-particle confinement fraction is assumed to be 0.95 for tokamak reactors, and 0.9 for helical reactor. The normalized beta value β_N is 4.0 for the reference tokamak design and 6.0 for the reference spherical tokamak design. The high temperature (~80 keV), high β_N (~10) plasma of the D^3He reactor should be based on optimistic assumption. For helical system the averaged beta value of 5% is assumed within the PEC simplified zero-dimensional power balance model with profile corrections. To justify the present simplified analysis, 1.5- or 2.0- dimensional equilibrium-transport predictive simulation code TOTAL [1] has been carried out for the physics projections to the TR, HR and ST designs.

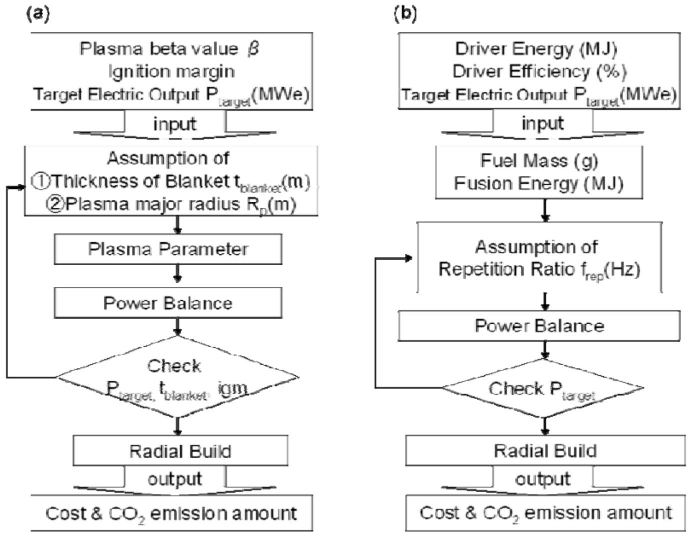

FIG. 2 Assessment flowcharts for (a) magnetic fusion energy (MFE) reactor and (b) inertial fusion energy (IFE) reactor.

As for engineering assessment, the maximum field strength of the superconducting magnet system is assumed 13 T made of Nb_3Sn conductors, except for maximum field strength of 8 T in ST normal conductor magnet. The superconducting magnet design scaling law is described in Ref. [6]. The optimistic maximum field of the future D^3He magnet is assumed 20 T. The tolerable neutron wall fluence is assumed to be 20MWYr/m^2 in the case of LiPb/SiC blanket system, which determines the replacement cycle of blanket modules.

The blanket thickness and the relevant gaps are critical parameters to determine the reactor radial build. We assume the reference scaling law of total blanket thickness as a function of neutron wall loading L_{wall} for liquid breeder blanket (Li/V, Flibe/FS, LiPb/SiC), and slightly thick scaling laws for solid breeder blanket (Li_2O/SiC). The thickness of fussion-fision (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.

Table 1 shows main parameters of reference magnetic confinement fusion reactors with LiPb/SiC blanket, obtained by the PEC code with the same electric power of $1GW_e$. In the tokamak reactors, the required current drive (CD) power might significantly contribute to the circulating power flow and bootstrap fraction f_{BS} is important.

(2) Inertial Fusion Reactors

The PEC system code has been upgraded to apply to IFE designs (Fig. 2(b)). In the case of IFE reactor [7,8], the fast ignition concept is adopted here based on KOYO-fast design. The driver energy and relevant efficiencies (driver efficiency ~0.075, compression efficiency ~0.05 and heating efficiency ~ 0.10) critically determine the fusion core system. 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.

$$E_{driver} = \frac{E_c}{\eta_c} + \frac{E_h}{\eta_h} \tag{1}$$

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

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

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

TABLE I: REFERENCE MAGNETIC CONFINEMENT FUSION REACTORS WITH 1GW ELECTRIC POWER, 30-YEAR OPERATION AND 75 % PLANT AVAILABILITY.

Type of Reactors	Tokamak	ST	Helical	Tokamak	Tokamak
*input	**TR (DT)**	**ST (DT)**	**HR (DT)**	**TR (F-F)**	**TR (D^3He)**
R_p / a_p*	**3.06**	**1.62**	**5.7**	**3.06**	**3.06**
$R_p /\langle a_p\rangle$*	**2.50**	**0.87**	**(7.8)**	**2.50**	**2.50**
T_0 [keV] *	**30**	**30**	**20**	**30**	**80**
$\langle\beta\rangle$[%] *	**(5.3)**	**(22.6)**	**5**	**(5.3)**	**(7.9)**
β_N*	**4**	**6**	**-**	**4**	**10**
ellipticity κ*	**2.0**	**3.5**	**2.0**	**2.0**	**2.0**
triangularity δ*	**0.5**	**0.5**	**-**	**0.5**	**0.5**
B_{max} [T] *	**13 (SC)**	**7.4 (NC)**	**13 (SC)**	**13 (SC)**	**20 (SC)**
R_p [m]	**5.97**	**4.00**	**14.0**	**5.06**	**7.85**
a_p [m]	**1.69**	**2.46**	**-**	**1.43**	**2.56**
$\langle a_p\rangle$ [m]	**2.39**	**4.62**	**2.1**	**2.02**	**3.14**
$\langle n_e\rangle$ [$10^{20}m^{-3}$]	**1.43**	**1.02**	**0.97**	**0.87**	**2.63**
$n_{e,crit}$	**1.50**	**1.20**	**1.17**	**1.38**	**1.34**
B [T]	**6.03**	**2.46**	**4.16**	**4.71**	**10.92**
I_p [MA]	**13.4**	**22.9**	**-**	**8.89**	**27.7**
f_{BS} [%]	**49**	**95**	**-**	**49**	**95**
τ_E [s]	**1.63**	**2.26**	**3.8**	**2.72**	**8.27**
H_H-factor	**1.31**	**1.67**	**-**	**2.32**	**4.25**
ISS H-factor	**-**	**-**	**5.01**	**-**	**-**
P_{fusion} [GW]	**2.62**	**3.21**	**1.87**	**0.59**	**2.74**
P_α [GW]	**0.52**	**0.64**	**0.38**	**0.12**	**-**
P_{CD}[GW]	**0.12**	**0.01**	**-**	**0.13**	**0.19**
$L_{neutron}$ [MW/m^2]	**3.11**	**3.87**	**0.89**	**0.97**	**0.97**
Blanket thickness [m]	**0.85**	**0.90**	**0.69**	**0.90**	**0**
Shield Thickness [m]	**0.36**	**0.39**	**0.30**	**0.39**	**0.6**
Wall Lifetime (Yr)	**4.6**	**3.7**	**16.0**	**11.0**	**13.3**

where R, ρ_C, α and T_h are plasma radius, compressed density, isentrope parameter (~3) and hot plasma temperature (~20keV), respectively. The compression and heating efficiencies are η_c (~0.05) and η_h (~0.1), respectively. Fusion energy E_{fus} is calculated by the fuel mass M_{fuel} and burn-up fraction Φ ,

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

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

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

The radius of IR cylindrical chamber R_{fw} should be determined by the detailed design analysis and might be a function of the neutron wall load $L_{neutron}$ nor fusion energy E_{fus}. Here we assumed the scaling laws derived based on previous ICF conceptual design works.

2.2. Cost Accounting Model

The cost analysis is mainly based on the unit costs per weight which values are based on those of Refs. [9-11]. 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 $0.114W_{TFC}$(t) [M$]. The other main detailed cost accounting values used here are described in Ref. [3]. Relevant to IR designs, costs of plant systems except driver and pellet fabrication systems are calculated by the same scaling data in the PEC code for MFE models. Here, the 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. [3].

TABLE II: COST, CO_2 AND EPR ANALYSIS FOR THREE REACTOR DESIGNS GIVEN IN TABLE I.

Type of MFE reactors	Tokamak	ST	Helical	Tokamak	Tokamak
	TR (DT)	**ST (DT)**	**HR (DT)**	**TR (Hybrid)**	**TR (D3He)**
< Cost [M$] >					
fusion island	**1056**	**1065**	**1823**	**1459**	**1185**
balance of plant	**1583**	**1817**	**1400**	**1500**	**1514**
Total capital cost	**5112**	**5582**	**6239**	**4645**	**5227**
< COE [mil/kWh] >					
capital cost	**75.6**	**82.5**	**92.7**	**68.6**	**76.2**
operations	**13.0**	**14.4**	**11.0**	**11.7**	**11.9**
fuel	**0.04**	**0.04**	**0.04**	**0.37**	**5.54**
replacement	**8.89**	**6.18**	**6.9**	**5.42**	**0**
decommissioning	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Total COE	**98**	**104**	**111**	**87**	**94**
< CO_2 emissions [kt] >					
fusion island	**288**	**129**	**439**	**470**	**537**
balance of plant	**628**	**692**	**577**	**607**	**609**
Construction total	**926**	**820**	**1016**	**920**	**1146**
< Rate [g-CO_2/kWh]>					
fusion island	**1.47**	**0.66**	**2.25**	**1.59**	**2.70**
balance of plant	**3.21**	**3.53**	**2.96**	**3.09**	**3.07**
operations	**3.16**	**3.16**	**3.16**	**3.16**	**3.16**
fuel	**0.24**	**0.25**	**0.45**	**0.50**	**2.73**
replacement	**0.34**	**0.74**	**0.26**	**1.30**	**0.01**
decommissioning	**0.78**	**0.78**	**0.78**	**0.78**	**0.78**
Total CO_2 Emission	**9.2**	**9.1**	**9.9**	**10.4**	**12.4**
< Energy Input [TJ] >					
fusion island	**2.2**	**2.2**	**3.1**	**1.8**	**2.9**
balance of plant	**10.8**	**11.4**	**18.2**	**7.5**	**6.8**
operations	**16.1**	**16.9**	**25.7**	**11.8**	**12.4**
fuel	**0.6**	**0.8**	**0.4**	**1.4**	**3.2**
replacement	**5.5**	**7.5**	**4.2**	**2.2**	**0.34**
decommissioning	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**
EPR	**19.3**	**18.1**	**12.1**	**27.3**	**26.6**

2.4. GHG Emission Model and Energy Payback Ratio Analyses

To estimate life-cycle CO_2 emission amounts equivalently including methane gas, we used basic unit for CO_2 weight (k-t-CO_2/t-material) based on input-output table [3,12-14]. GHG emissions from mining, transportation and fabrication of various components are totally included in this table.

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 the CO_2 emission amount. The calculation procedure for IFE is almost same as that of MFE reactors.

The energy profit ratio (energy payback ratio, EPR) is the ratio of energy output to input and is often used to indicate the feasibility of extracting energy from a given resource. In this paper, preliminary analysis has been done as an extension of Ref.[1].

3. Assessment Results

3.1. Beta Dependence for Tokamak Reactors with Different Blanket Designs

The reactor scale is determined by the plasma beta, the radial build and the thickness of the blanket and shield is strongly related to this radial build in MFE reactor designs. Table II shows the assessment results of MFE reference reactors with liquid breeder LiPb/SiC design. 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 GHG emission of D^3He reactor using lunar helium is higher than that of DT reactors because of larger plasma major radius R_p and higher power current-drive requirements, as well as lunar helium 3 fuel processing and transportation (300\$/g-^{3}He, 180 kt-CO2/t-^{3}He) [15].

3.2. Driver Energy Dependence for Inertial Fusion Reactors

TABLE III REFERENCE INERTIAL FUSION REACTOR WITH FLIBE BREEDER LIQUID WALL.

Net electric power P_{enet} (MW)*	**1000**
Driver energy E_{driver} (MJ)*	**1.2**
Driver efficiency η_{driver}*	**0.075**
Target gain G_{pel}	**180**
Mass of fuel M_{fuel} (mg)	**2.1**
Repetition rate f_{rep} (Hz)	**12**
Number of module	**3**
Chamber size R_{fw} (m)	**3.5**
Total thermal output (GW)	**2.84 (0.95x3)**
Recirculation power (GW)	**0.18**
Averaged $L_{neutron}$ (MW/m^2)	**2.72**
Total fusion power P_{fus} (GW)	**2.64**
Total capital cost (M\$)	**5050**
COE (mil/kWh)	**107**
CO2 (g-co2/kWh)	**12.9**
EPR	**30.6**

* input parameter

Table III shows the assessment result of IFE plant 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. Here, the assumed driver energy is 1.2 MJ based on KOYO design assuming the laser diode cost of 3 yen/W. The blanket exchange rate is assumed 2 times lower than that of MFE designs, and the COE and CO_2 emission rate are found to be lower than those of MFE models when the cost of laser diode is as lower as 1 yen/W.

3.3. Assessment of Higher Power Plants

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), as well as by increasing beta value.

Figure 3 shows the effect of net electric fusion power increase on COE and CO_2 emission

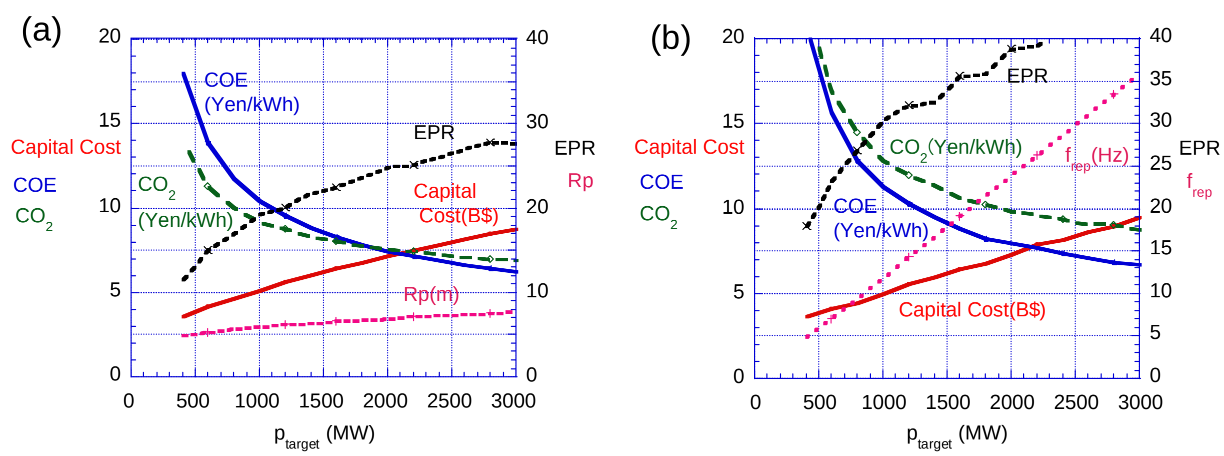

FIG. 3 GHG life-cycle emission from (a) 1GWe MCF reactors depending on beta value. Larger circles denote reference designs. (b) 1GWe ICF reactors depending on driver energy.

rate. The major radius of TR should be increased from 6.0m to 7.7m to raise net electric power from 1GW to 3 GW. In this case COE and CO_2 unit emission are reduced from 10.4 yen/kWh to 6.2 yen/kWh, and 9.2 g-CO_2/kWh to 6.9 g-CO_2/kWh, respectively. As for IR, the power dependences of these values are almost same as those of TR. Despite of the difference of reactor types, the COE reduction is larger than the CO_2 unit emission reduction when the net electric power is increased.

3.4. Scaling Formula for COE and CO2 Emission Rate

In the system analysis we confirmed the advantage of high-beta TR designs in COE [1]. After wide parameter scans, we obtained the following new COE and life-cycle GHG emission rate scaling formulas for TR and HR as functions of electric power P_e (1~3GW), plant availability f_{avail} (0.65~0.85), normalized beta β_N (3~5) or averaged beta $<\beta>$ (3~5%), maximum magnetic field strength $B_{\max}$ (10~16 T), thermal efficiency f_{avail} (0.37~0.59) and operation year t_{oper} (20~40 Year);

$$COE^{TR}[\mathrm{mil/kWh}] = 10^{2.09}\frac{1}{P_e^{0.48} f_{avail}^{0.90} \beta_N^{0.40} B_{\max}^{0.12} f_{th}^{0.32} t_{oper}^{0.78}}$$

$$COE^{HR}[\mathrm{mil/kWh}] = 10^{3.96}\frac{1}{P_e^{0.50} f_{avail}^{0.93} <\beta>^{0.31} B_{\max}^{0.60} f_{th}^{0.26} t_{oper}^{0.84}}$$

$$CO_2^{TR}[\mathrm{g-CO_2/kWh}] = 10^{1.60}\frac{1}{P_e^{0.26} f_{avail}^{0.43} \beta_N^{021} B_{\max}^{0.05} f_{th}^{0.25} t_{oper}^{043}}$$

$$CO_2^{HR}[\mathrm{g-CO_2/kWh}] = 10^{2.57}\frac{1}{P_e^{0.26} f_{avail}^{0.53} <\beta>^{0.33} B_{\max}^{0.63} f_{th}^{0.35} t_{oper}^{0.54}}$$

The root mean square errors of these scaling laws are less than 2% for TR and less than 3% for HR. The COE of HR depends on the maximum field strength different from that of TR. The parameter dependence of CO_2 emission rate is rather weak than that of COE, except for beta, maximum field strength and thermal efficiency of HR on GHG emission rate.

For IR design, the same scaling formulas for COE and GHG emission rate are given by

$$COE^{IR}[\mathrm{mil/kWh}] = \frac{10^{3.23}}{P_e^{0.51} f_{th}^{0.33} f_{avail}^{0.90} t_{oper}^{0.75} (\frac{1}{\alpha_F})^{0.23}}$$

$$CO2^{IR}[\mathrm{g-CO_2/kWh}] = \frac{10^{2.34}}{P_e^{0.31} f_{th}^{0.25} f_{avail}^{0.37} t_{oper}^{0.39} (\frac{1}{\alpha_F})^{0.18}}$$

which is obtained as functions of electric power P_e (1~3GW), plant availability f_{avail} (0.65~0.85), thermal efficiency f_{th} (0.37~0.59), operation year t_{oper} (20~40 Year) and isentrope parameter α_F (2~4). The root mean square errors of these IR scaling laws are less than 1%. To reduce COE of IR, the increase in availability, operation period and net electric power is important. However, these effects on the GHG emission rate reduction are not so strong comparing with the COE reduction, which is same as the TR case. That is the reason why the CO_2 emissions from the concrete (0.12 t-CO_2/t-material) and the steel structure materials (1.4 t-CO_2/t-material) are rather dominant.

3.5. Comparisons with Other Electric Power Generation Systems

By comparing fusion reactors with other electric power generation systems [9-10] from the view point of COE and CO_2 emission amount, we confirmed that fusion reactor emits less CO_2 amount (Fig.4). Therefore, there is little influence of introducing carbon tax on economics of fusion reactors.

When the carbon tax of around 3,000 yen/t-CO_2 is introduced, the COE of fusion reactor might be at the same level on that of coal-fired electric power plant without CCS (Carbon dioxide Capture and Storage) system and 1.5 times lower than that of oil-fired electric power plant.

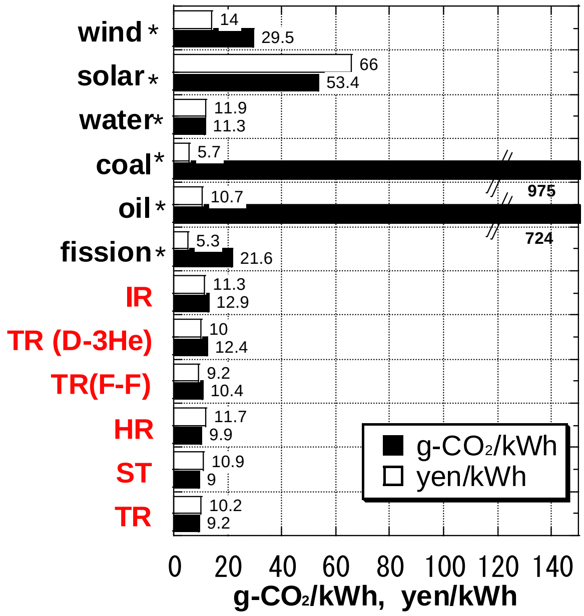

FIG.4 COE and GHG emission comparisons among fusion reactors and other electric power systems
**: from Ref.[9]*

By introducing CCS to coal or oil based generation systems, the target cost by 2030 is around ~3,000 yen/t-CO_2 and corresponds to the above-stated carbon tax level. The COE will be increased by ~1-2 yen/kWh in the construction of CCS for new fossil-fuel electric power generators.

4. Summary

In order to search for economically and environmentally optimized fusion reactors, and to find out scaling formulas of cost of electricity and CO_2 emissions on key reactor parameters, system analyses of typical 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 fusion-fission hybrid blanket and advanced D-^{3}He fuels are assessed in these analyses.

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. Especially, new scaling formulas for the reference TR, HR and IR plants are introduced. The parameter dependence of CO_2 emission rate is rather weak than that of COE, except for beta, maximum field strength and thermal efficiency of HR on GHG emission rate. The favorable 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 fission power plant. On the other hand, the life-cycle CO_2 emission amount from fusion reactor is slightly less than that of fission power plant. The fusion-fission hybrid reactor and advanced D^3He reactors are evaluated, and their future advantages are clarified.

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. Even if the CCS technology is applied to new fossil power plants, both magnetic and inertial fusion energy rectors are expected to be advantageous against global warming.

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