Environmental and Economical Assessment of Various Fusion Reactors by the Calculation of CO_2 Emission Amounts

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We compared the CO_2 emissions of several fusion reactors. The magnetic confinement systems evaluated here are the tokamak reactor (TR), helical reactor (HR), and spherical tokamak reactor (ST). These models are calculated by the Physics-Engineering-Cost (PEC) code. The inertial confinement fusion reactor (IR) is also evaluated, assuming its driver energy and driver efficiency. In addition, different blanket modules and fuels are considered in the TR designs. To calculate life-cycle CO_2 emission from fusion reactors defined by plasma parameters and radial build, we used a basic unit for CO_2 weights (kt-CO_2/t-material). Calculation results indicate that CO_2 is emitted mainly in the construction stage of superconducting magnet systems for magnetic confinement fusion reactors. For the IR design, the driver system construction and pellet fabrication stages involve considerable CO_2 emission. By comparing fusion reactors with other electric power generation systems in terms of CO_2 emission, we confirmed that fusion reactors emit less CO_2. Therefore, introducing a carbon tax has little effect on the economics of fusion reactors, and the cost of electricity (COE) from fusion reactors might be lower than that of oil-fired electric power plants when a carbon tax of around several hundred yen/t-CO_2 is introduced.

Keywords: tokamak reactor (TR), helical reactor (HR), spherical tokamak reactor (ST), inertial confinement fusion reactor (IR), blanket, CO_2 emission amount, cost of electricity (COE)

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1. Introduction

Fusion reactors are expected to be sources of abundant clean energy in the future. To realize a fusion energy system, many technological problems must be solved. In addition, it is essential to assess the safety, economics, and environmental burden of fusion reactors compared with other power generation systems. In this paper, we calculate the cost of electricity (COE) and CO_2 emission amounts for several types of fusion reactors using the Physics-Engineering-Cost (PEC) code [1, 2]. We clarify major components contributing to large CO_2 emission amounts in each reactor design. In particular, as an extension of our assessment of magnetic fusion reactors [3], we evaluate various blanket designs, including fission-fusion hybrid and D-^{3}He fuel fusion systems. An inertial confinement fusion reactor is also assessed by adding driver and target models to the PEC code. To assess economic and environmental issues simultaneously, we consider the effect of the introduction of a carbon tax on the COE of various electric power plants and clarify the advantage of fusion reactors.

2. Assessment procedures

Here we evaluate three types of magnetic confinement fusion reactors [the tokamak reactor (TR), helical reactor (HR), and spherical tokamak reactor (ST)] and the inertial confinement fusion reactor (IR). Several blanket modules and fuel systems (D-T or D-^{3}He) are considered in TR design. We used the PEC code [1–3] to calculate the COE of magnetic confinement fusion reactors. The PEC code is a system code that calculates the plasma parameters and radial build of fusion reactors with input parameters such as net electric power output and ignition margin.

The design optimization procedure and its results for TR, HR, and ST designs have been described in Refs. [1,2]. In this paper, we add an IR assessment scheme to the PEC code. The flow chart for calculating IR parameters is shown in Fig. 1. The fast ignition concept is considered here. The mass of fuel M_{fuel} that would be compressed and heated is estimated for a given driver energy

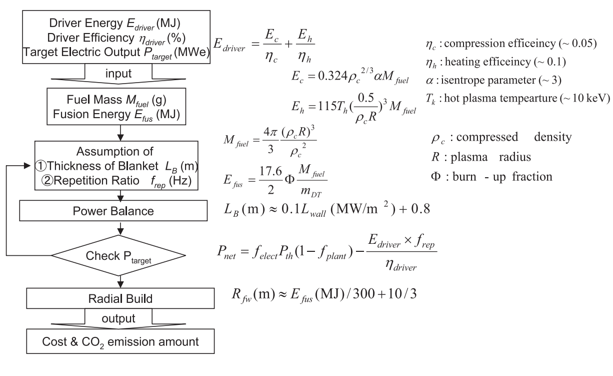

Fig. 1 Assessment flow chart for inertial confinement fusion reactor.

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E_{driver} and driver efficiency η_{driver}. The fusion energy E_{fus} is calculated from the fuel mass, and the repetition rate f_{rep} is adjusted to satisfy power balance. Chamber size R_{fw} is determined by referring to examples of other reactor designs [4, 5]. The costs of plant systems, except for the driver system and pellet fabrication, are calculated by the same scaling as the PEC code. The driver system cost ($163E_{driver}$ + 113 [M\$]) and pellet fabrication cost $\left(132\left(\frac{f_{rep}(\mathrm{Hz})}{5.6}\right)^{0.7}+66[\mathrm{M\$}]\right)$ are given by the scaling described in Ref. [5]. To estimate CO_2 emission amounts, we used a basic unit for CO_2 weight (kt-CO_2/t-material) based on an input-output table [3, 6, 7]. All CO_2 emissions from mining, transport, and fabrication of various components are included in this table.

3. Assessment models

The reactor designs depend strongly on physics and engineering constraints, and typical reactor designs were chosen in Refs. [1, 2] for the TR, HR, and ST. To compare all the fusion reactors under the same conditions, 1 GW net electric power output, a 30-year operation period, and 0.75 plant availability are assumed.

In the reference case, the normalized beta value (average beta value for HR) is determined by the physics performance of reactor models. In the case of a TR with D-^{3}He fuel, high temperature and a high maximum toroidal field are required for a compact, economical reactor. Thus, a D-^{3}He fuel reactor is assumed to have high performance (high temperature, strong magnetic field, and high beta). Because of the low D-D neutron generation rate of D-^{3}He fuel operation, we assumed that there is no blanket exchange for D-^{3}He fuel fusion reactors. The main parameters of magnetic confinement fusion reactors calculated by the PEC code are listed in Table 1.

In the reference case of an IR, driver energy and driver efficiency are assumed to be those of the Kr-F laser in the SIRIUS-P design [4]. A Li breeder liquid wall chamber is adopted for the IR, and its lifetime criterion against neutron irradiation is assumed to be two times longer than that of conventional blanket designs for a TR, HR, and ST. The main parameters of the reference IR design are listed in Table 2.

For TR systems, we evaluated five typical blanket modules: a Li breeder with a V structural material blanket (Li/V), a Flibe breeder with a ferrite steel structural material blanket (Flibe/FS), a LiPb breeder with a SiC structural material blanket (LiPb/SiC), a Li_2O breeder with a SiC structural material blanket (Li_2O/SiC), and a fission-

Table 2 Main parameters of reference inertial confinement fusion reactor. The blanket module assumed here is a Li breeder liquid wall.

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

Table 1 Main parameters of several magnetic confinement fusion reactors obtained by the PEC code. Identical electric output (1,000 MWe), operation period (30 years), and plant availability (0.75) are assumed here to compare all the reactors consistently.

	TR		ST	HR
confinement scaling	ITER Elmy H mode			ISS mode
fuel	D-T	D-^{3}He	D-T	D-T
normalized β-value β_N / average β-value $<\beta>$ (%)*	$\beta_N = 4$	$\beta_N = 6$	$\beta_N = 6$	$<\beta> = 4\%$
Aspect ratio $<A>$*	3.5	3.5	1.6	7.8
Average temperature $<T>$ (keV)*	15	42.5	15	10
Plasma major radius R_p (m)	6.3	13.9	4.3	14.9
Toroidal field B_t (T)	6.2	8.4	2.5	4.7
Total fusion power P_{fus} (GW)	3.48	4.82	4.19	2.35
Average density $<n>$ (10^{20}/m^3)	1.5	1.5	1.0	1.0

* input parameter

Table 3 Parameters of several blanket used in TR design.

Blanket module	Li/V	Flibe/FS	LiPb/SiC	Li_2O/SiC	F-F hybrid
Thermal efficiency $\eta_{thermal}$ *	0.46	0.4	0.5	0.49	0.4
FW/Blanket lifetime W_{life} (MWy/m^2)*	18	15	20	20	15
Toroidal field B_t (T)	6.1	6.2	6.1	5.9	4.7
Total fusion power P_{fus} (GW)	2.91	3.48	2.62	2.68	0.59
Thickness of FW/Blanket $t_{blanket}$ (m)	0.4	0.6	0.8	0.5	0.9
Thickness of shield t_{shield} (m)	0.8	0.7	0.4	0.8	0.6
Neutron wall load L_{wall} (MW/m^2)	3.0	3.3	2.8	2.7	0.9
Blanket cost intensity (M$/m^3)*	0.23	0.45	0.34	0.34	0.64
Blanket CO2 emission intensity (kt-CO_2/m^3)*	0.220	0.022	0.036	0.036	0.022

* input parameter

fusion hybrid (F-F hybrid) blanket [8]. The F-F hybrid blanket model includes UO_2, so its neutron energy multiplication rate is very high (we assumed a rate of 6.0). Each blanket model has a different thermal efficiency and wall lifetime in the PEC code [3]. The main parameters of several TR reactors with different blanket modules are shown in Table 3.

4. Assessment results

The results of life-cycle CO_2 emission calculation for the reference fusion reactors are shown in Fig. 2. The coil construction phase is the main CO_2-emitting stage of magnetic confinement fusion reactors. CO_2 emission during coil system construction accounts for 10 %, 8 %, and 20 % of life-cycle CO_2 emission amounts of a TR, ST, and HR, respectively. HR and D-^{3}He fueled TR systems need a larger coil than D-T fuelled TRs and STs, and greater amounts of CO_2 are emitted in the fusion island (FI) construction stage. An ST needs more re-circulating power, including ohmic loss at the normal conducting coil system, and more CO_2 is emitted at the balance of plant (BOP) construction stage of an ST. In contrast, an HR requires less re-circulating power, so less CO_2 is emitted in the BOP construction stage. The dependence of CO_2 emission amounts and plasma major radius on the beta value are shown in Fig. 3. Achieving a higher beta value leads to a more compact system and less CO_2 emission.

CO_2 emission amounts of TRs with different blanket modules are shown in Fig. 4. The value of thermal efficiency is an influential factor in fusion reactor design. A model with higher thermal efficiency, such as the LiPb/SiC or Li_2O/SiC model, can lead to a more compact system and less CO_2 emission than other blanket models. Vanadium fabrication requires considerable electrical power, so the CO_2 emissions of the Li/V blanket model are somewhat higher than those of other blanket systems. The F-F hybrid blanket model may have modified FI requirements because of its high neutron multiplication factor. Therefore, it might be possible to construct its reactor with lower cost and less CO_2 emission. However, high-level radioactive waste disposal poses another problem.

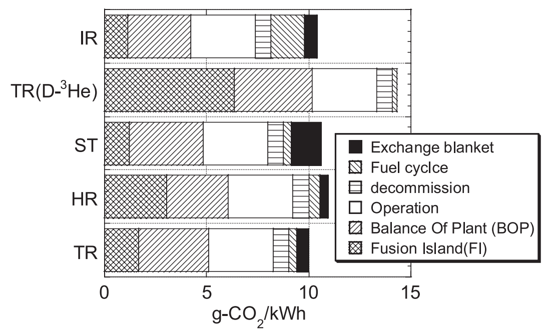

Fig. 2 2 Life-cycle CO_2 emission amounts from a D-T-fuelled tokamak reactor (TR), helical reactor (HR), spherical tokamak reactor (ST), inertial confinement reactor (IR), and D-^{3}He-fuelled tokamak reactor [D-^{3}He (TR)].

Driver construction is the most critical CO_2-emitting stage of an IR. Furthermore, in the fuel cycle stage, an IR

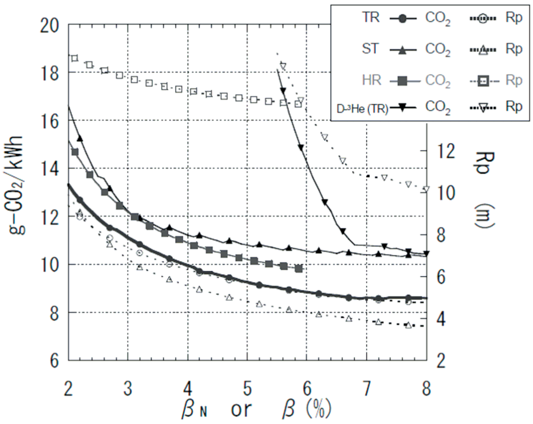

Fig. 3 Dependence of CO_2 emission amount and plasma major radius R_p on normalized beta value β_N [for TR, ST, D^{3}He (TR)] or average beta value β(for HR).

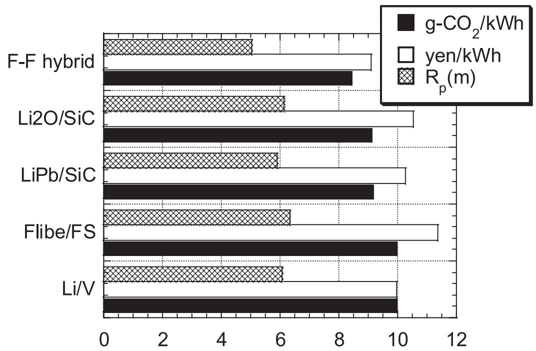

Fig. 4 CO_2 emission amount, cost of electricity (COE), and plasma major radius R_p of several TR designs with different blanket modules.

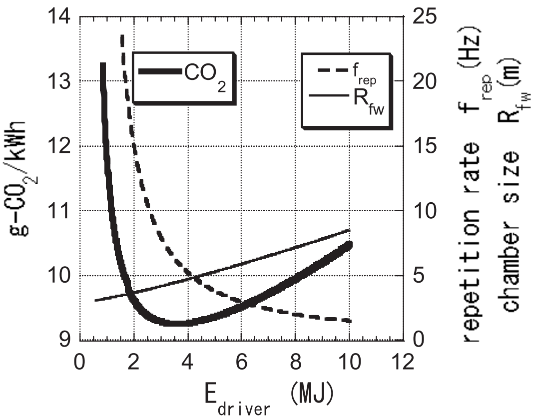

Fig. 5 Dependence of CO_2 emission amount, laser repetition rate f_{rep}, and chamber size R_{fw} on input driver energy E_{driver} in an IR.

emits more CO_2 than a magnetic confinement fusion reactor. However, total CO_2 emissions from an IR are lower than those from magnetic confinement fusion reactors because of its compactness. The dependence of CO_2 emission amount, laser repetition rate f_{rep}, and chamber size (first wall radius) R_{fw} on input driver energy are shown in Fig. 5. When the driver energy is lower, a higher laser repetition rate is necessary to attain the desired net electrical power because the pellet gain is small. A somewhat high laser repetition rate f_{rep} requires many pellets, and CO_2 emission during the fuel cycle is assumed to be increased as $132\left(\frac{f_{rep}(\mathrm{Hz})}{5.6}\right)^{0.7} + 66[\mathrm{kt\text{-}CO_2}]$. In contrast, when a higher driver energy is assumed, the driver construction stage involves much more CO_2 emission. In addition, a larger chamber size is necessary to tolerate a higher fusion heat pulse load.

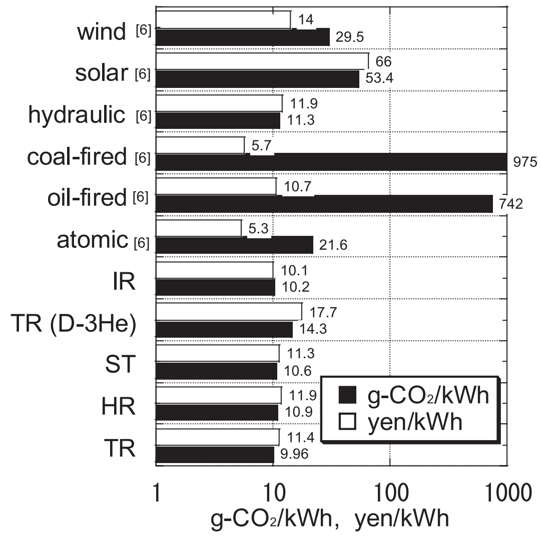

Fig. 6 Comparison of COE and CO_2 emissions for fusion reactors and other conventional electric power plants.

Figure 6 compares the COE and CO_2 emissions of fusion power plants and other power generation systems. Fusion reactors emit less CO_2 than other conventional power plants do [7]. In comparison with a fusion reactor, an atomic power plant emits more CO_2 in its fuel cycle. An atomic power plant needs uranium concentration, whereas a D-T fusion power plant needs tritium separation. In this paper, tritium separation of the fusion reactor might be optimistically evaluated, so it might be necessary to reconsider it well in the future.

The COE of fusion reactors and other power plants in the case of carbon tax introduction is shown in Fig. 7. The amount of CO_2 emission from a fusion reactor during its life cycle is far less than those from thermal power plants. Thus, the introduction of a carbon tax has little effect on the COE of fusion reactors, as is also the case for conventional clean energy resources like solar and wind power systems. The carbon taxes assumed in Fig. 7 are 1350, 3808, 655, and 2300 yen/t-CO_2 (actual example of Norway, actual example of Sweden, Japanese environmental ministry plan, and Central Research Institute of the Electric Power Industry recommendation [9], respectively).

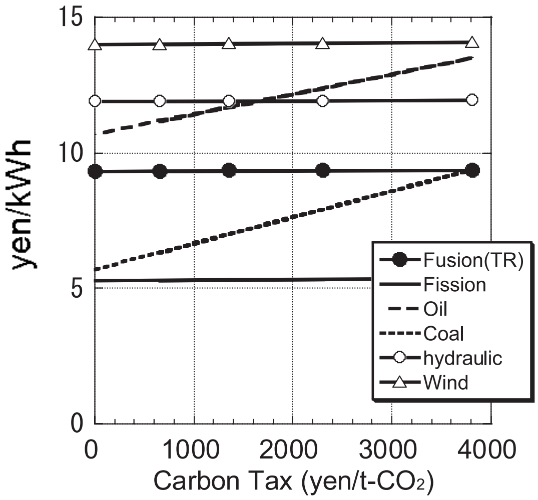

Fig. 7 COE of fusion reactor (TR) and other electric power plants in the case of carbon tax introduction.

5. Summary

We calculated the amount of life-cycle CO_2 emission from various fusion reactors, including an inertial confinement fusion reactor. CO_2 is emitted mainly in the magnet system construction stage for magnetic confinement fusion reactors. D-T fuelled HR and D-^{3}He fuelled fusion reactors, which have bigger magnet systems, have higher CO_2 emission during construction. The FI of an ST is so compact that less CO_2 is emitted during its construction, but the BOP construction stage involves considerable CO_2 emission because of its large re-circulating power. For IRs, CO_2 is emitted mainly in the driver system construction stage. The chamber size related to the neutron wall load and the pellet fabrication determined by the repetition rate are also strongly related to CO_2 emission amounts. After comparing fusion reactors with other power generation systems in terms of CO_2 emission amounts, we conclude that fusion reactors emit less CO_2. Even if a carbon tax is introduced, it will have little influence on the economics of fusion reactors, unlike the case of conventional coal and oil electric power plants. The COE of fusion reactors might be lower than that of oil-fired electric power plants when a carbon tax of around several hundred yen/t-CO_2 is introduced.

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