Economical and Life-Cycle Energy Assessment of Magnetic Fusion Power Reactors[*)]

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We analyzed several types of fusion reactors, tokamak (TR), spherical tokamak (ST), helical (HR), and inertial fusion reactor (IR) using physics, engineering and cost (PEC) code, which evaluates economic and life-cycle energy amount quantitatively. We compared the cost of electricity (COE) and the energy payback ratio (EPR) of each fusion reactors with those of fission power plant. Especially, we focus on the EPR of TR with several blanket and shield designs having scarce materials such as silicon carbide (SiC), vanadium alloy (V), and ferritic steel (FS). As the result, we found that the EPR of TR with SiC/LiPb blanket/shield model is the lowest. The COEs and the input energy of TR ($\beta_N = 4.0$) and IR are lower than those of ST and HR. The COE of fusion reactor is two times higher than that of fission power plants. However the EPR of fusion reactor is as high as that of fission reactor.

Keywords: EPR, COE, tokamak reactor, helical reactor, spherical reactor, inertial fusion reactor, blanket

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1. Introduction

In order to realize the fusion energy plant, high social acceptability is required. But, fusion reactors might require enormous amount of construction costs and scarce materials. Here, we evaluated the cost of electricity (COE) and energy payback ratio (EPR) of fusion reactors. The COE is an index evaluating whether fusion reactor construction cost is appropriate or not. And, the EPR is an index evaluating how a power plant produces the energy effectively from the lower input energy. In the previous study, we evaluated the COEs and EPRs of tokamak (TR), helical (HR), and spherical tokamak (ST). In this study, we analyze the EPRs of fusion reactors which include inertial fusion reactor (IR). Moreover, we compare the EPRs of fusion reactors with those of other electric power plants.

2. Analysis Method

Magnetic fusion reactors and the inertial confinement fusion reactor (IR) were designed using PEC (physics engineering and cost) system code [1]. In the case of magnetic fusion power reactors, the input parameters are the target electrical power (typically 1 GWe) (P_{target}), normalized beta (β_N) and so on. In the plasma physics part of the PEC code we calculate the plasma major radius which is able to achieve the target electrical power. Then, the fusion island weight and the total cost are evaluated. Using the PEC code for IR, we calculate the fuel mass for reaction (M_{fuel}(g)) from input parameters relevant to implosion and heating process. Then, we get the fusion pulsed energy (E_{fus}(MJ)) and driver energy (E_{in}(MJ)). The fusion power (P_{fus}(MW)) of IR is calculated from fusion pulsed energy multiplied by repetition ratio. The chamber size of IR is estimated by the scaling formula obtained from several fusion power plant designs, and the fusion island weight and the total cost are evaluated.

The COE is defined as the cost for the 1kWh electric energy production. In this study, we carried out the life cycle assessment (LCA) from resources supply to decommissioning.

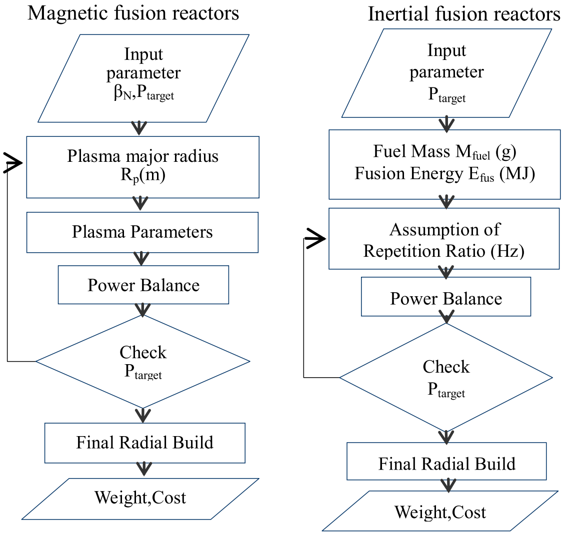

Fig. 1 Flowchart of PEC code.

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[*)] This article is based on the presentation at the 21st International Toki Conference (ITC21).

Table 1 Typical energy intensity used in this study.

	material or inter-industry table name	Unit	Energy intensity
Magnet	Nb_3Sn	TJ/m^3	0.202
Magnet (ST)	Al	TJ/t	0.163
	Cu	TJ/m^3	0.038
Vacuum vessel	SUS	TJ/t	0.147
Turbine	Turbine	TJ/M$	6.319
Cooling system	Refrigerating machines	TJ/M$	5.490
Laser Glasses	Other glassware	TJ/M$	9.293

2.1 Energy payback ratio (EPR) definition

The EPR means energy output efficiency. The EPR is defined as the ratio of electrical output energy to input energy. The definition of the EPR is as follows:

$$EPR = \frac{E_{\text{output}}}{E_{\text{const.}} + E_{\text{operation}} + E_{\text{fuel}} + E_{\text{replace}} + E_{\text{Decom.\&Decon.}}} \tag{1}$$

The denominator shows the total input energy; fusion power plant construction ($E_{\text{const.}}$) including fusion island (FI) and balance of plant (BOP) which consist of more than 20 components, management and operation ($E_{\text{operation}}$), fuel production (E_{fuel}), replacement (E_{replace}) and decontamination and decommissioning of reactor equipment ($E_{\text{Decom.\&Decon.}}$). Above all the construction input energy investments are evaluated from the weight or the cost of components multiplied by energy intensity shown as Table 1 [2, 3]. The components of the fusion island are blanket, shield, diverter, vacuum vessel, toroidal field coils, support structure, and so on. The balance of plant is the system which produces electric power from thermal power, for example, turbine, coolant system and so on. The costs of these systems are evaluated from several scaling formulas as a function of thermal power (P_{th}).

2.2 Blanket and shield models

The role of blanket is to take out thermal power from fusion reaction, and blanket materials persist against high thermal heat load and low activation materials should be used. In the reactor designs, three typical structure materials, SiC, V, and FS have been used. But these materials are highly scarce, and much energy might be consumed. Thus, we analyze the EPRs of TR with three typical blanket/shield models. Table 2 shows the blanket and shield models related to the specific designs; ARIES-AT [4] shown as A, ARIES-RS [5] shown as B, SSTR [6] shown as C. The energy intensity is calculated from each original blanket/shield mass and volume fraction. The thickness of each blanket and shield ($t_{\text{blanket+shield}}$) is evaluated from scaling formula with respect to the neutron wall load (L_{neutron}), $t_{\text{blanket+shield}} = 0.1L_{\text{neutron}}+0.8$ (m). The ratio of blanket thickness to shield thickness is evaluated from each blanket and shield design. The replacement cycle of the blanket is decided by the relationship of neutron wall load and permissible neutron fluence at the first wall.

Table 2 Three blanket models.

	A	B	C
Structure/breeder/ coolant/multiplier	V/Li/ Li/-	SiC/LiPb/ LiPb/-	FS/Li_2O /H_2O/Be
Energy intensity [TJ/t]	0.804	0.222	0.526
Thermal efficiency [%]	46	50	34.5
Neutron fluence at first wall [MWy/m^2]	15	18.5	15

Table 3 Typical reactor parameters for TR, ST, HR.

	TR	TR	ST	HR
R_p/a_p,*$R_p/(a_p)$	3.06	3.06	1.6	5.7*
κ	2.0	2.0	3.54	2.0
β_N,*(β)[%]	4.0	3.0	7.96	4.0*
T_0[keV]	30	30	30	20
$B_{\max}$ [T]	13	13	10	13
thermal efficiency f_{elect}	0.5	0.5	0.46	0.5
P_{th} [MW]	2393	2627	3212	2065
P_{enet}[MW]	993	991	993	991
R_p [m]	4.75	5.28	3.36	13.31
blanket space [m]	0.76	0.74	0.89	0.62
density limit ratio	0.49	0.43	2.06	0.91
L_{neutron} [MW/m^2]	2.93	2.62	4.71	0.83
H_H-factor	1.37	1.13	2.28	-
I_{bs}/I_p	0.60	0.40	0.95	-
Fusion Island weight [t]	6599	8116	3312	15886

Table 4 Typical reactor parameters for IR.

	IR
compression fuel/pellet mass density ρ_c [g/cm^3]	300
hot spot areal density ρR_h [g/cm^2]	0.5
hotspot temperature T_0 [keV]	20
fusion isentrope α	3
fusion pulsed energy E_{fus} [MJ]	205
fuel mass for reaction M_{fuel} [mg]	2.00
laser repetition rate f_{rep} [Hz]	8.4
driver energy E_{in} [MJ]	1.15
pellet gain G_{pel}	177
net electric output P_{enet} [MW]	991
first wall radius R_{fw} [m]	3.33
neutron wall load L_{neutron} [MW/m^2]	3.96
fusion island weight [t]	7112

2.3 Reactor parameters

The reactor parameters used in this study are shown in Table 3 and Table 4. In both tables, input parameters are shown above the center line, and output parameters from PEC code are given below the center line.

First, we evaluate the COEs and the EPRs of TR with the three blanket models. After then, we evaluate the COE and the EPR of typical reactor designs with B-blanket model.

3. Results

Table 5 shows the COEs and EPRs of TRs with three blanket/shield models. We designed these TRs to have the input parameters shown in Table 3 for TR (β_N = 4). The COEs of the three models differ slightly, and the TR with blanket B has the highest EPR value.

Model B's EPR is the highest because of two reasons. First, it has a higher thermal efficiency than the others, as shown in Table 2. Consequently, the major radius is smaller and the size of the equipment required for balance of plant (BOP) is reduced. Thus, the radius of model B shown in Table 5 is the smallest. Blanket A also has high thermal efficiency, but the total input energy investment is high.

Second, the input energy of the blanket and shield in model B is low. Because vanadium alloy and liquid lithium materials are used in blanket A, the energy intensity of model A might be high. As shown in Fig. 2, the FI and replacement input energy investment of model B are the lowest. Therefore, as shown in Fig. 3, its shield input energy is the lowest. This is because of a specific design feature of model B: the blanket is thicker than the shield. By the difference of blanket and shield model, the change in total energy is about 15%. The blanket and shield in model B are clearly better in terms of the COE and EPR. Therefore, we focused on typical reactor designs with blanket B.

Table 5 COEs and EPRs of three TR (β_N = 4) designs with different blanket models.

	A	B	C
R_p[m]	4.85	4.75	5.23
blanket ratio of $t_{\text{blanket+shield}}$	0.3	0.7	0.4
COE [mil/kWh]	8.6	8.7	9.6
EPR	26	33	26

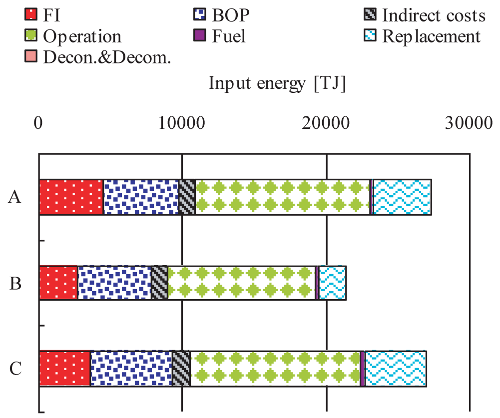

Fig. 2 Total input energy breakdown for TRs with three blanket shield models.

Next, we evaluated the COEs and EPRs of four typical reactor designs: TR (β_N = 3,4), ST, HR, and IR. The COEs and input energy of TR (β_N = 4) and the IR are lower. Here we discuss the input energy of each reactor in detail. We show their input energy breakdowns in Fig. 4. In magnetic fusion reactors, we consider the FI, BOP, and indirect costs such as machine construction costs. The FI input energy of the ST is the lowest, and the total construction input energy of TR (β_N = 4) is the lowest. This is because the radius of the ST is the smallest, and the FI weight is the lowest. However, the ST requires high thermal fusion power to compensate for the large ohmic power loss in the conducting coils, which increases the BOP input energy. Thus, the input energy for the FI is lowest, but the input energy for ST construction is higher than that of TR (β_N = 4). The difference in input energy between TR (β_N = 3) and TR (β_N = 4) is due to the difference in the bootstrap current fraction (Table 5). Thus, the input energy for the FI and replacement in TR (β_N = 3) is higher than that of TR (β_N =

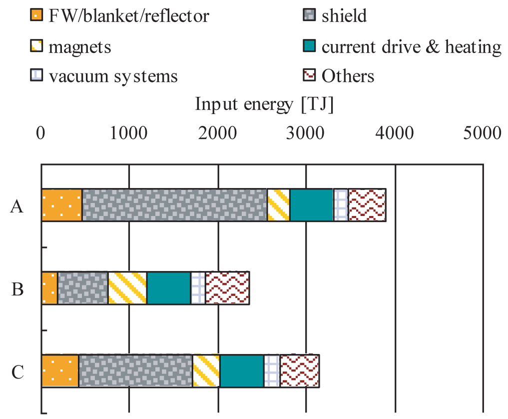

Fig. 3 Fusion island input energy breakdown for TRs with three blanket shield models.

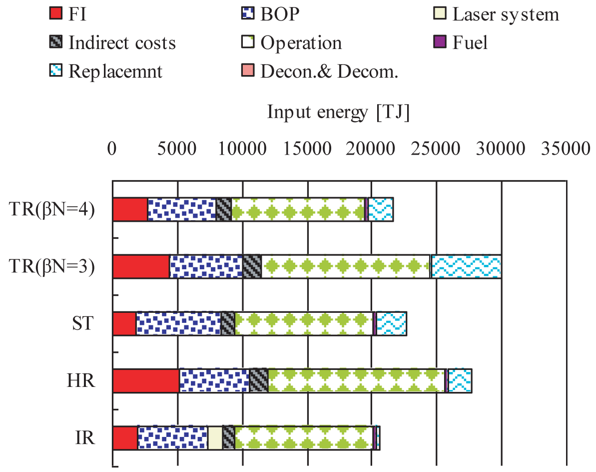

Fig. 4 Input energy breakdown for each reactor.

Table 6 Comparison with other electric power plants.

	TR (β_N=4)	ST	HR	IR
COE [yen/kWh]	8.8	9.1	10.8	7.5
EPR	33	31	26	34
	TR (β_N=3)	fission	oil	solar
COE [yen/kWh]	11.4	5.9	10.2	46~66
EPR	24	*28.2	7.9	5.2

* Gas Centrifuge Plant

4). The HR can operate in the steady state, but the plasma major radius is about 13 m, and the input energy for the FI is rather high. In the IR, we consider the FI, BOP, laser system, and indirect costs such as construction. The input energy for the FI is as low as that of the ST because the radius of the IR is almost the same as that of the ST. The designed FI is simple, and the shield is assumed to use graphite, which has low energy intensity. In addition, the input energy for the laser system with a diode-pumped solid-state laser is about 2000 TJ. The input energy for the laser system accounted for the increase in the total input energy with increasing driver energy. Moreover, the construction input energy for the IR is the same as those of the TR and ST. In the IR design, we assume that 20% of the blanket and the laser optics are replaced every two years. Although the replacement frequency for the IR is high, the input energy for replacement is lower than that of magnetic fusion reactors. Thus, the total input energy of the IR is the lowest.

Finally, we compared the COEs and EPRs of fusion reactors with those of other electric power plants (fission, oil, and solar) from [7], as shown in Table 6. The EPRs of fusion reactors are the same as that of fission power plants, which are more energy efficient than other electric power plants. Conversely, the COEs of fusion reactors are twice those of fission power plants.

4. Summary

We evaluated the COEs and EPRs of several magnetic fusion reactor designs, such as a TR, ST, and HR, and extended our analysis to the IR. We mainly used the SiC/LiPb blanket/shield model because it has the lowest input energy. The EPRs of TR ($\beta_N = 4$) and the IR are higher than those of several other fusion reactors. The advantage of the IR is its low input energy for FI construction and replacement because of its simple structure. Therefore, in this study, the IR has the lowest COE and highest EPR among the fusion reactors. For ST reactors, the input energy for the FI is lowest, and the BOP input energy is high because of the power loss from ohmic heating of the normal conducting coils. Thus, it is required to evaluate a superconducting ST design in the future.

Finally, we compared the COEs and EPRs of fusion reactors with those of other electric power plants. The COE of fusion reactors is almost 10 Yen/kWh, which is higher than those of other large power plants. Conversely, the EPR of fusion reactors is as high as that of fission reactors and is higher than that of other power plants.

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