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Japanese government has set the goal of reducing CO_2 emission in 2050 by 80% below the 1990 level. To achieve this goal, various measures should be taken. The GTHTR300, a commercial High Temperature Gas-cooled Reactor (HTGR) design being developed by Japan Atomic energy agency, offers a wide spectrum of heat applications by using its high temperature heat up to 950℃. The potential contribution of CO_2 emission reduction by HTGR is estimated by considering the amount of CO_2 emission reduction through domestic deployment of the GTHTR300 for hydrogen production and related applications and for industrial heat supply and by taking carbon credit through international deployment of the GTHTR300 for hydrogen production and related applications and for seawater desalination. The best estimate for domestic CO_2 reduction is 2.07×10^8 t-CO_2/y and that from oversea CO_2 reduction is 2.25×10^8 t-CO_2/y. The sum of domestic and international contribution by the HTGR is about 47% of the 9.13×10^8 t-CO_2/y national reduction target in 2050, for which deployment of 52 plants in Japan and 113 plants abroad, with each plant containing four 600 MWt reactor units, is required.

Keywords: HTGR, Nuclear Heat Utilization, Hydrogen, CO_2 Emission Reduction, Desalination, Carbon Offset, Carbon Credit

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2050年における日本の二酸化炭素排出量削減目標に対する高温ガス炉の寄与に関する研究

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我が国では、地球温暖化対策の一環として、2050年までに80%以上の二酸化炭素（CO_2）排出量の削減を目標として掲げている。これを達成するためには、省エネやコージェネレーション、CO_2フリーエネルギーの導入など、様々な対策を実施する必要がある。日本原子力研究開発機構では、水素製造や蒸気供給、海水淡水化など、発電のみならず950℃までの多様な熱利用が可能な高温ガス炉に関する研究を進めており、これまでに実用高温ガス炉の基本設計であるGTHTR300を提案している。本稿では、我が国のCO_2排出量削減に係る高温ガス炉のポテンシャルを明らかにするため、国内へのGTHTR300導入による水素製造や熱利用、産業へのプロセスヒート供給、ならびに海外でのGTHTR300導入による水素製造、熱利用、海水淡水化により得られるカーボンクレジットを用いたCO_2削減量を算出した。その結果、国内では、年間2.07億トンのCO_2削減、海外では、年間2.25億トンのCO_2削減となり、合計すると2050年のCO_2削減目標である9.13億トンの47%に相当する4.32億トンが削減可能となる。これに相当する高温ガス炉は、熱出力600MWtの高温ガス炉を4基有するプラントが国内へ52プラント、海外に113プラント必要となる。

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1. CO_2 emission reduction goals of Japan

The world population expanded by 25% in the last 20 years. Currently at 7.3 billion, it will expectedly reach 9.7 billion in 2050 [1]. In the meantime, the standard of living has kept rising with the world average gross domestic product (GDP) per capita doubling in the last two decades.

The growth in population and economy pushed up energy demand by 40% during the same period. According to the International Energy Agency (IEA). The world primary energy production stood at 13,600 Mtoe (5.69×10^8 TJ) in 2013, of which fossil fuels accounted for 81.6%. Between 2012 and 2013, production of coal increased by 4.6%, oil by 0.5% and natural gas by 2.7%.

The global energy-related CO_2 emission is 32.9 Gt in 2013. In the business-as-usual "Reference Scenario", it would increase to 45.9Gt in 2050 [2]. The atmospheric concentration of CO_2-quivalent would reach 760-860 ppm in 2100 with the resulting global warming of 2.8-4.0^{o}C from the 1850-1900 pre-industrial level.

In the "Advanced Technologies Scenario" in which a mix of technological options including efficiency improvement, renewable energy, carbon capture and sequestration, and nuclear energy, are to be deployed, CO_2 emission would be reduced to 23.3 Gt in 2050. Expanded use of nuclear energy is expected to contribute to 11% of the reduction.

In the "Innovative Technologies Scenario" where proactive development and deployment of innovative technologies including Generation-IV nuclear reactors will be required [2], the global CO_2 emission would be halved by 2050 from the 2013 level so as to restrict the atmospheric concentration of CO_2-quivalent to the 450 ppm level is needed to achieve the target of the December 2015 Paris UN Framework Convention on Climate Change (COP21) agreement to limit the global warming to less than 2^{o}C.

Joined by other 195 countries at the COP21, Japan has committed the Intended Nationally Determined Contribution (INDC) of reducing greenhouse gas (GHG) emissions by 26% in 2030 below the 2013 level. In longer-term, the April 2012 Basic Environment Plan of Japan has set the goal of reducing CO_2 emission by 80% below the 1990 level (Table 1-1).

To achieve the reduction goals, a combination of measures such as transforming energy efficient buildings and promoting cogeneration and a bottom-up calculated domestic energy mix including renewable, nuclear, fossil fuel with CCS will be determined. A global warming action plan based on law is planned to be drafted [3].

In addition, Japan has established the Joint Crediting Mechanism (JCM), also known elsewhere as Carbon Offsetting, to facilitate contribution of Japan's low-carbon technologies, products, systems, services and infrastructure as well as implementation actions, to sustainable development of developing countries and to account for the GHG reductions and removals of such contribution as Japan's emission reduction. Currently Japan has JCM agreement in place with 16 countries including Saudi Arabia, Indonesia, Vietnam, Myanmar, Mexico and others. Developed countries such as South Korea, Canada, Switzerland, and EU similarly use or are considering possible use of international carbon offsetting to achieve their domestic CO_2 reduction targets.

2. Potential roles of HTGR contribution to Japan's CO_2 emission reduction

The Basic Energy Policy, issued by the Government of Japan (GOJ) in April 2014 [4], spells out the roles of HTGR as follows

> *"Under international cooperation, GOJ also facilitates R&D of nuclear technologies that serves the safety improvement of nuclear use, such as high-temperature gas-cooled reactors which are expected to be utilized in various industries including hydrogen production and which has an inherent safety."*

Accordingly, this study quantifies the roles of HTGR industrial applications including hydrogen production and heat supply to various industrial sectors as a means to contribute to meeting Japan's CO_2 emission reduction target in 2050.

Hydrogen promises being an alternative fuel because it can be produced in large quantity and used in places where fossil fuels are used but without emitting carbon dioxide. Apart from some 60 million metric tons of hydrogen consumed annually worldwide today, mainly in oil, petrochemical and steel sectors, hydrogen use has begun to spread in residential and transport sectors in many countries and regions.

In Japan, general marketing of residential fuel cell appliances such as Ene-Farm began in 2014, followed by fuel cell vehicles (FCV) in 2015. FCVs are foreseen to account for 40% of all vehicles on road by 2050. The demand for hydrogen fuel is estimated to be as high as 25 million tons annually by 2050. Hydrogen is regarded as an essential component of Japan's strategy to meet the CO_2 emission reduction target [3]. On the other hands, there are many problems to realize "hydrogen society", for instance, large-scale hydrogen production and supply method, infrastructure, cost and so on.

Japan Atomic Energy Agency (JAEA) has developed the baseline design of the commercial High Temperature Gas-cooled Reactor (HTGR), GTHTR300C (refer to Fig. 2-1). The GTHTR300C may cogenerate hydrogen using thermochemical water splitting IS (Iodine- Sulfur) process. The hydrogen amount produced is given in Table 2-1.

The domestic potential of the GTHTR300C hydrogen production is assessed based on the demand forecast of IEEJ for hydrogen by 2050 in the four major economy sectors of road transportation, industry, commercial and residential and power generation [5]. This study shows that a substantial yet reasonable share of the demands in these sectors may be provided by hydrogen produced by the GTHTR300 whereas the balance would be provided by other carbon free and neutral sources of renewable energy and fossil energy with CCS.

The reactor coolant temperature range of the HTGR up to 950℃ covers the temperature requirement of the heat demand by various process heat industries. This study focuses on examining the potential of supplying carbon-free nuclear heat to major domestic high-temperature heat users including oil refining, coal production, and chemical industry, thereby contributing to reducing CO_2 emissions in these industrial sectors.

The roles of deploying the GTHTR300C overseas as a means of contribution to Japan's CO_2 emission reduction target rely on the premise of JCM described earlier. While nuclear energy is a significant component of the INDCs of established nuclear-power countries including the US, China, and Japan, many countries such as Saudi Arabia and Indonesia do not include nuclear energy in their INDCs. This would make the amount of carbon offsetting gained through the JCM-sanctioned export of the innovative HTGR systems eligible to count as Japan's CO_2 reduction. And the climate fund that Japan has pledged to provide to developing countries and to support innovation through "Actions for Cool Earth 2.0" may be utilized to finance the deployment of HTGR overseas.

The HTGR overseas deployment is focused on promoting the activities of production and application of hydrogen in the three economy sectors of road transportation, commercial and residential and steelmaking. These sectors are considered because Japan holds technologically competitive edge with FCVs, stationary fuel cell units, and direct reduction steelmaking. The demands for hydrogen are based on the world primary energy demand and steel production output, of which a varying fraction is assumed to be supplied by the hydrogen produced by the GTHTR300C.

Further, the HTGR overseas deployment will also examine the large seawater desalination because a case that the HTGR can be successfully deployed overseas to take the credit of carbon offset back to Japan can be made. JAEA studies have shown that the HTGR based desalination offers particularly strong cost and business incentives over today`s prevailing methods that consume fossil fuels [6]. In particular, an innovative desalination proposal by JAEA [7] is shown capable of cost-competitively producing water by only utilizing the waste heat of the HTGR power plant. This technology of desalination could be deployed in the Middle East region. The region accounts for the majority of seawater desalination markets. Many countries in the region have the stated policies of seeking nuclear desalination. Yet some of these countries such as Saudi Arabia have not include nuclear desalination in their INDCs.

3. Domestic contribution of CO_2 emission reduction

3.1. CO_2 reduction by hydrogen utilization

3.1.1. Hydrogen demand

Forecast for future hydrogen demand in Japan is summarized in Table 3-1, in which transportation, industries and residential, power generation and steelmaking are considered as the hydrogen consumers. The references in the table identify the sources used in the forecast. Details of the forecast are explained for individual sector in the following.

(1) Transportation

Fuel cell vehicles (FCVs) will replace current ICE passenger cars, cargo cars and buses (except kei cars) by 2050 as follows [5];

- 2025: Beginning of spread (10% of new car sales)
- 2040: 19% of total cars (50% of new car sales)
- 2050: 40% of total cars (100% of new car sales)

Hydrogen demand is then estimated by calculation from the assumptions of average travel distance, tank-to-wheel fuel efficiency and the number of FCVs.

(2) Industrial and residential sectors

These sectors currently use stationary fuel cells that are fueled by hydrogen produced from natural gas or city gas. However, CO_2-free hydrogen should be used in the future to meet the target of GHG reduction. Therefore, CO_2-free hydrogen fuel cell (H_2FC) spread scenario is assumed as below;

- 2025: Beginning of H_2FC spread
- 2050: Full spread of H_2FC, i.e., 100% of fixed fuel fells

Hydrogen demand is then calculated taking into account of the power generation efficiency of the fuel cell system and the power generation share of H_2FC units in the industrial and residential sectors.

(3) Power generation

As for the power generation, Matsuo et al. estimated that the hydrogen power generation will be commercialized after 2030, and rapidly spread to replace fossil-fired plants and nuclear power plants (light water reactor, LWR) [5]. On the other hand, the Agency for Natural Resources and Energy in Ministry of Economy, Trade and Industry of Japan has stated that nuclear power will meet 20-22% of the total domestic electricity demand in FY2030 [8]. We assume that nuclear power would generate 20% of the total national electricity demand even after FY2030 using only LWR because most of electricity generated from HTGR would be consumed by hydrogen production and that hydrogen power generation supplies 27% of the total electricity demand in 2050. As shown in Table 3-1, power generation accounts for about 50% of the total hydrogen demand forecast in 2050.

(4) Steelmaking

The steel making considers the hydrogen direct reduction steelmaking process [9]. The conventional process of direct reduction consumes natural gas. We assume that this process is replaced by commercially-developed hydrogen reduction process by 2050. The hydrogen demand for steelmaking in 2050 is calculated as 27% of total steel production in Japan.

3.1.2. CO_2 reduction potential

Table 3-2 summarizes the estimated amount of CO_2 emission reduction by all domestic hydrogen uses described above. The details of CO_2 reduction estimates are described in the following.

(1) Transportation

Fig.3-1 shows the amount of CO_2 emission reduction by FCV, which is estimated from the hydrogen demand of the transportation sector shown in Table 3-1. By taking into account of the difference in tank-to-wheel efficiency between FCV and internal combustion engine vehicle (ICEV), the estimation of CO_2 reduction is below;

$R_{CO2}=Ef_{H2}/\eta_{ICEV}/Ho_{gas}*E_{gas}$

Where,

Ef_{H2}: Final energy consumption of hydrogen $Ef_{H2}=D_{H2}*Ho_{H2}*\rho_{H2}*\eta_{FCV}$
D_{H2}: Hydrogen demand
Ho_{H2}:Higher heating value of hydrogen = 142.18 MJ/kg
ρ_{H2}:Density of hydrogen = 0.08988 kg/m^3
η_{FCV}: Tank to wheel efficiency of FCV = 59%
R_{CO2}: CO_2 reduction rate
Ho_{gas}: Higher heating value of gasoline = 47.2 MJ/kg
E_{gas}:CO_2 emission intensity of gasoline = 3.17 kg-CO_2/kg-gasoline
η_{ICEV}: Tank to wheel efficiency of ICEV = 23%

As the result, utilization of hydrogen for FCVs can potentially reduce 0.73×10^8 t/y of CO_2 in 2050.

(2) Industrial and residential sectors

Fig.3-2 shows the amount of CO_2 emission reduction by fixed fuel cell in industrial and residential sectors, which is estimated from the hydrogen demand of these sectors shown in Table 3-1. It is calculated based on the expected efficiency of PEFC [5] and current efficiency of hot water dispenser such as EcoCute [11] and LNG-fired power generation as below;

$$R_{CO2}=Ef_{H2}/\eta_{Fossil}/Ho_{LNG}*E_{LNG}$$

Where,

Ef_{H2}: Final energy consumption of hydrogen $Ef_{H2}=D_{H2}*Ho_{H2}*\rho_{H2}*\eta_{FC}$
D_{H2}: Hydrogen demand
Ho_{H2}:Higher heating value of hydrogen = 142.18 MJ/kg
ρ_{H2}:Density of hydrogen = 0.08988 kg/m^3
η_{FC}: Total efficiency of PEFC = 90%
R_{CO2}: CO_2 reduction rate
η_{Fossil}: Total efficiency of fossil fuel = 67%
Ho_{LNG}: Higher heating value of LNG = 55.21 MJ/kg
E_{LNG}:CO_2 emission intensity of LNG = 2.71 kg-CO_2/kg-LNG

As a result, 0.36×10^8 t/y of CO_2 will be reduced in 2050 by utilization of fixed fuel cell in the industrial and residential sectors.

(3) Power generation

Power generation sector emitted 42% of total CO_2 emission from fossil-fired plants in FY2013 [12]. Utilizing hydrogen as an alternative fuel to replace the fossil-fired plants would thus represent a significant route of CO_2 emission reduction [5]. Hydrogen power generation has the biggest demand for hydrogen of all sectors as shown in Table 3-1. In this study, fossil-fired plants are assumed to be coal-fired plants. The CO_2 emission reduction is calculated by the following equation:

$$R_{CO2} = D_{H2} * Ho_{H2} * \rho_{H2} / Ho_{Coal} * E_{Coal}$$

Where,

R_{CO2}: CO_2 reduction rate
D_{H2}: Hydrogen demand
Ho_{H2}:Higher heating value of hydrogen = 142.18 MJ/kg
ρ_{H2}:Density of hydrogen = 0.08988 kg/m^3
Ho_{Coal}: Higher heating value of coal = 26.6 MJ/kg
E_{Coal}:CO_2 emission intensity of coal = 2.41 kg-CO_2/kg-Coal

As a result, hydrogen power generation is estimated to reduce 1.35×10^8 t/y of CO_2 emission in 2050 as shown in Fig. 3-3.

(4) Steelmaking

Conventional steelmaking process emits huge amount of CO_2 at a rate of 1.9 t-CO_2/t-iron which is averaged value of all iron production in the world. Steel production in Japan in 2012 was 107.2 million t/y for both domestic uses and export. In this study, the amount of steel production output in Japan is assumed to grow up to 148.2 million t/y in proportional to world population growth rate. Fig. 3-4 shows the estimated CO_2 emission reduction as a function of the fraction of the hydrogen direct reduction of the total steel output. The function is calculated as follows:

$$R_{CO2} = I * E_{Iron}$$

Where,

R_{CO2}: CO_2 reduction rate

I: Amount of iron production by hydrogen direct reduction process

E_{Iron}: average CO_2 emission intensity from fossil steelmaking = 1.9 t-CO_2/t-iron

As the result, the hydrogen steelmaking may reduce CO_2 emission by 0.76×10^8 t/y in the case of 27% share and 2.88×10^8 t/y in the case of 100% share.

3.1.3. Summary of CO_2 reduction by GTHTR300 hydrogen production

The GTHTR300 is assumed to meet one-third to one half of the total hydrogen demand whereas the balance is assumed to be met by renewable energy and fossil fuel with CCS hydrogen resources. This corresponds to one third to one half of the total CO_2 reduction of all sectors given in Table 3-2. Specifically, the GTHTR300 could potentially reduce 1.32 to 1.90×10^8 t/y, corresponding to 14.5% to 20.8% of the national CO_2 emission goal in 2050, as shown in Fig. 3-5.

3.2. CO_2 reduction by heat supply for industries

Fig.3-6 shows the energy consumption amount and CO_2 emission in industry sector in 2013 [10,13]. The steel, petroleum & coal production and chemical accounts for more than two third of the total heat demand. Most of heat consumed in steel industry is used for heating furnaces at temperature range of 1000°C, beyond the range of the HTGR heat supply. In addition, for simplicity this study neglects the heat demands of ceramic and pulp & paper because their shares of heat demand are relatively small. Therefore, Only the heat demands by chemical and petroleum & coal production industries are considered to be supplied by the GTHTR300. The share of the GTHTR300 supply is assumed to be 25%～50% of their total energy consumption and CO_2 emission is reduced accordingly. As a result, the CO_2 reduction of 0.34～0.69 $\times10^8$ t/y can be reduced by the GTHTR300 heat supply.

4. Overseas contribution of CO_2 emission reduction

This section estimates the contribution of CO_2 reduction by exporting the GTHTR300 and related technology in developing countries and by counting the reduction and removal of CO_2 emission as Japan's CO_2 reduction through the JCM.

We consider hydrogen production to forecast demands overseas. In addition, we consider heat supply in desalination market, for the reason given in Section 2. We do not consider heat process users because they are most based on conventional technologies that are beyond the scope of the JCM. Lastly, hydrogen power generation is not considered because no reliable forecast can be found for this application.

4.1. Hydrogen and desalination demand

Future hydrogen demand and seawater desalination demand of the world (without Japan) are forecast as shown in Table 4-1. They are explained for each of the sectors as follows.

(1) Transportation and fixed fuel cell

Hydrogen demand of transportation and fixed fuel cell is estimated $24{,}517\times10^8$ Nm^3/y at 2050 by Ishimoto et al. [14]. As for the transportation sector, it is assumed that the world transportation demand will increase with growth of economy. After 2030, electric cars, hydrogen FCVs, and biodiesel vehicles will gradually penetrate in the transportation market. The hydrogen is assumed to cover 24% of energy consumed in the transportation sector in the world at 2050.

As for the stationary sector, it is assumed that the current use of natural gas, biomass and high grade coal will continue to be the main source of energy in the sector in the world and that the use of hydrogen will account for only 2% of the total stationary energy consumption in 2050.

(2) Steelmaking

World steelmaking amount was 1,559.2 Mt/y in 2012 [15]. Assuming that the world steelmaking output would increases with the population growth from 2012 to 2050 [1], the steel production would reach 2,156.0 Mt/y in the world or 2,007.8 Mt/y excluding

Japan’s production.

The Midrex technology, the hydrogen direct reduction steelmaking process [9], is invented by Japan. Currently the process consumes natural gas and produces about 5% of the world annual steel [16]. It is assumed that hydrogen will fully replace natural gas as reduction material and fuel used in the process by 2050 while the share of steel output by the direct reduction process remains at 5% of the world total steel production while excluding Japan’s. As a result, the hydrogen demand is estimated to be 705×10^8 Nm^3/y for direct reduction steel making in 2050.

(3) Desalination

The combined desalination demand for Saudi Arabia, UAE and Kuwait was 9,125 Mm^3/y at 2010 [17]. Nearly all demand is seawater desalination. These countries account for the majority of demand in the Middle East region and 38% of the world desalination demands that include large and small plants and are not limited to seawater desalination. Since we limit the scope of the GTHTR300 to the large seawater desalination, we select the reference demand in 2010 to be that of the fore-mentioned three countries. To predict the future desalination demand, we assume that the demand would increase in proportion as the forecast GDP growth of the Middle East [2]. As a result, the desalination demand for Middle East is estimated to be 32,128 Mm^3/y in 2050.

4.2. CO_2 reduction potential

Table 4-2 summarizes the CO_2 emission reductions from hydrogen uses in FCV and fixed FC, from hydrogen direct reduction steel making and from nuclear desalination.

(1) FCV and Fixed FC

Table 4-2 shows potential amount of CO_2 emission reduction by FCV and fixed FC in the world, which is calculated by meeting the hydrogen demands shown in Table 4-1. The calculation considers the difference of tank-to-wheel efficiency between FCV and ICEV. The fixed FC assumes the performance of the hot water dispenser such as EcoCute [11] and LNG-fired power generation as was considered earlier in the domestic estimation.

As a result, making use of hydrogen for FCV and fixed FC can potentially reduce 51.33×10^8 t/y of CO_2 in the world by 2050. To take carbon credit through JCM, we limit to the markets of Middle East and ASEAN. Assuming that the GTHTR300 will be deployed to meet 10% to 30% of the hydrogen demands in these markets, it would result in carbon offset for Japan of 0.45×10^8 to 1.36×10^8 t/y.

(2) Steelmaking

Conventional steelmaking processes involve intensive fossil fuel and CO_2 emission. On average, conventional steelmaking emits 1.9 ton-CO_2 per ton of steel [9]. To reduce CO_2 emission from steelmaking, we consider nuclear energy steelmaking which uses only hydrogen and electricity produced by the GTHTR300C [18]. The amount of CO_2 reduction calculated from application of the GTHTR300C-based steelmaking is shown in Fig. 4-1 as a function of the share of world steelmaking forecast while excluding Japan's. The calculation is as follows;

$$R_{CO2}= I*E_{Iron}$$

Where,

R_{CO2}: CO_2 reduction rate

I: Amount of iron production by the hydrogen direct reduction process

E_{Iron}: CO_2 emission intensity from steelmaking = 1.9 t-CO_2/t-iron

For example, if nuclear energy steelmaking replaces 1% to 5% of the world conventional steelmaking output (without Japan), it can generate carbon offset for Japan of 0.38×10^8 to1.91×10^8 t/y.

(3) Desalination

While the most fossil and nuclear thermal desalination cogeneration plants operated to date need to compete for live steam consumption with steam turbine, thus reducing turbine power output, this is completely avoided in a GTHTR300C desalination cogeneration proposal made by JAEA [7]. In essence the proposal makes efficient use of waste heat from the gas turbine as cost free energy for desalination.

The CO_2 reduction is calculated as follows:

$R_{CO2} = r * D_{H2O} * Q * E_{fossile}$

Where,

R_{CO2}: CO_2 reduction rate

r: GTHTR300 desalination install ratio

D_{H2O}: Desalination demand

Q: Heat demand for fossil desalination = 173MJ/m^3-H_2O

$E_{fossile}$: CO_2 emission intensity of coal, natural gas and crude oil = 0.0702 kg-CO_2/MJ

As a result, the GTHTR300 desalination replaces 10% to 30% of the desalination demand in Table 4-1, it would generate carbon offset for Japan of 0.39×10^8 to 1.18×10^8 t/y.

4.3. Contribution of CO_2 reduction from GTHTR300 overseas deployment

Fig. 4-2 summarizes the contribution of GTHTR300, which sums up the minimum and maximum of the CO_2 reduction in each of the markets analyzed above. Thus, the contribution of the GTHTR300 overseas deployment through taking carbon credit with the JCM amounts to minimum of 1.23×10^8 t/y to maximum of 4.44×10^8 t/y.

5. Conclusion

This study demonstrates a large potential of HTGR to contribute to Japan's CO_2 emission reduction goal in 2050. Fig. 5-1 shows the best estimation of the contribution to CO_2 emission reduction by GTHTR300 in 2050.

The best estimation for domestic contribution of 2.07×10^8 t-CO_2/y assumes that 40% of domestic hydrogen demand and 40% of selected heat demand is met by the GTHTR300. Of the total domestic contribution, 1.52×10^8 t-CO_2/y is from hydrogen production and the balance is heat production. The total number of GTHTR300 plants to be required are 52 plants with each plant containing four 600 MWt reactor units.

To arrive at the best estimate from overseas contributions, the medium of minimum and maximum cases obtained in section 4.3 is assumed in the markets of the FCV, fixed FC and desalination sector while 30% of the maximum case is assumed for the steelmaking market. As a result, the best estimation for the total overseas contribution of CO_2 reduction is 2.25×10^8 t-CO_2/y. The total number of GTHTR300 plants to be required is 113 plants with each plant containing four 600 MWt reactor units.

In sum, the HTGR offers to potentially reduce 4.32×10^8 t-CO_2, equivalent to 37.9% of Japan's national CO_2 emission in 1990, by realizing the best scenarios of domestic and overseas deployment for the GTHTR300.

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[14] IAE, Study of Demand for CO_2-free Hydrogen in Japan and the World, Journal of the Japan Institute of Energy, 2015.

[15] World steel association, World steel in figures 2014.

[16] Midrex Technologies, Inc, 2014 World Direct Reduction Statics.

[17] Global forecast and analysis, Desalination Markets 2010.

[18] X. Yan et al., Study of a nuclear energy supplied steelmaking system for near-term application, Energy, Vol. 39, pp.154-165, 2012.

Table 1-1 CO_2 emission reduction goals of Japan

				COP21 INDC target of Japan (December 2015)	Basic Environmental Plan of Japan (April 2012)
Year	1990	2005	2013	2030	2050
Energy-related CO_2 emission (million t-CO_2)	1,070	1,290	1,334	1,042 (26% of 2013 level)	214 (80% of 1990 level)

Table 2-1 Production parameters per GTHTR300 reactor

Reactor thermal power	600 MWt			
Reactor coolant temperature	950°C			850°C
Power generation	202 MWe	88 MWe		274 MWe
Heat supply to hydrogen production	170 MWt	370 MWt	-	-
Hydrogen production	26,666 Nm^3/h	58,750 Nm^3/h	-	-
Heat supply to process heat	-	-	370 MWt	
Recoverable waste heat to desalination	157 MWt	-	-	220 MWt
Desalination capacity	40,000 m^3/d	-	-	55,000 m^3/d

Table 3-1 Future hydrogen demand in Japan

	2030	2040	2050	References
Transportation(FCV)	56	169	330	[5]
Industries & Residential (Fixed FC)	15	146	429	[5]
Power Generation (H_2 Fired)	0	923	1,167	[5,8]
steelmaking	0	0	314	[9,10]
Total	71	1,238	2,240	（10^8 Nm^3/y）

Table 3-2 Summary of CO_2 emission reduction by domestic hydrogen use

（10^8 t/y）

	2030	2040	2050
FCV	0.12	0.37	0.73
Fixed fuel cell	0.01	0.12	0.36
Power generation	0	1.07	1.35
Steelmaking	0	0	0.76
Total	0.13	1.56	3.20

Table 4-1 World hydrogen and desalination demand (without Japan)

		2030	2040	2050	Reference
FCV and Fixed FC	10^8 Nm^3/y	2,539	6,956	24,517	[14]
Steelmaking	10^8 Nm^3/y	-	-	705	[6], [15]
Desalination	Mm^3/y	19,958	25,322	32,128	[2], [17]

Table 4-2 Summary of CO_2 emission reduction by world hydrogen use

（10^8 t/y）

	2030	2040	2050
FCV and Fixed FC	5.32	14.56	51.33
Steelmaking	-	-	1.91
Desalination	2.43	3.09	3.92

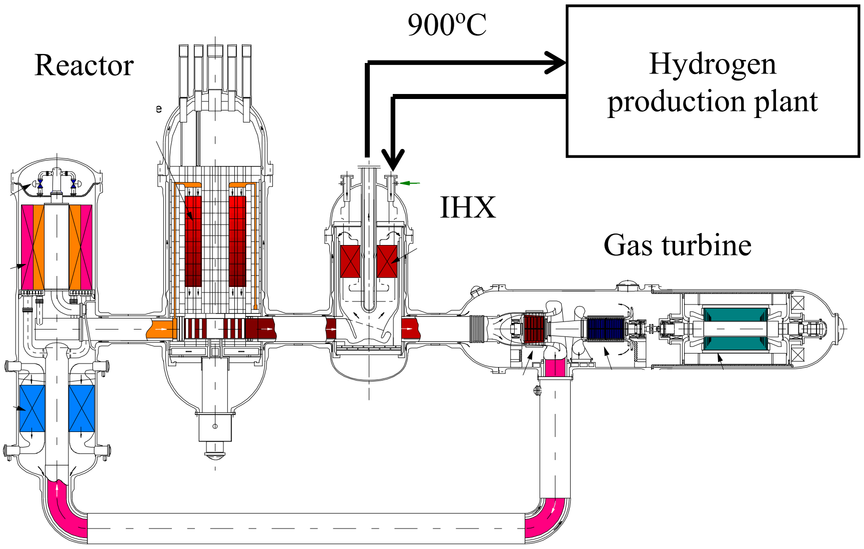


Fig.2-1 GTHTR300C system design — *Hydrogen is produced using 900°C heat supplied in the IHX. Up to 370MWt of the 600MWt reactor thermal power may be supplied to the hydrogen plant with the balance used by the gas turbine to circulate the reactor coolant while generating electric power for in-house consumption and for serviced industrial and community users.*

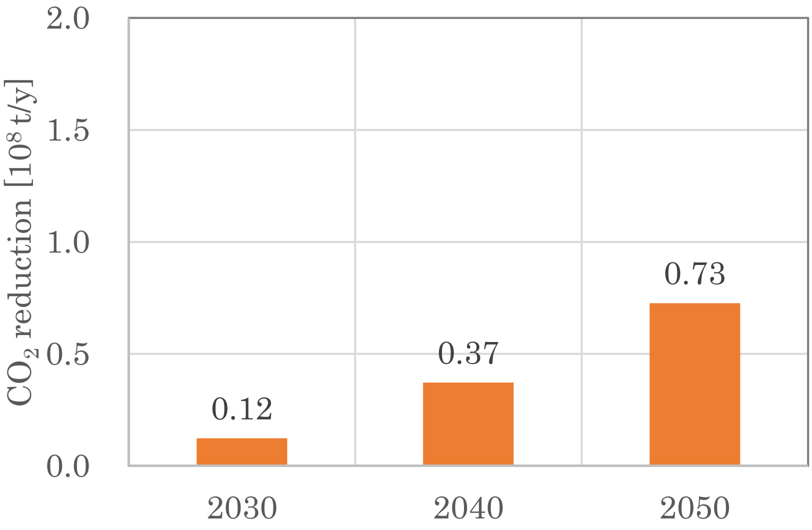


Fig.3-1 CO_2 reduction in transportation

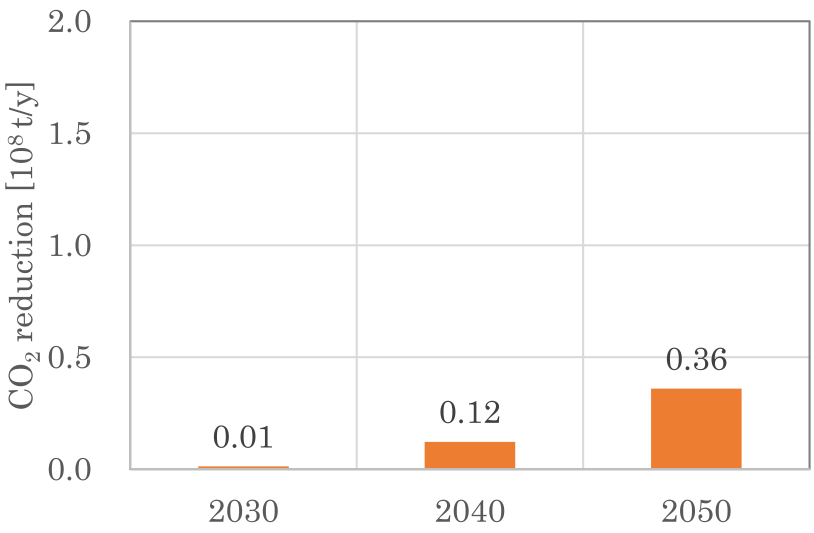


Fig.3-2　Amount of CO_2 reduction in industrial and residential sectors

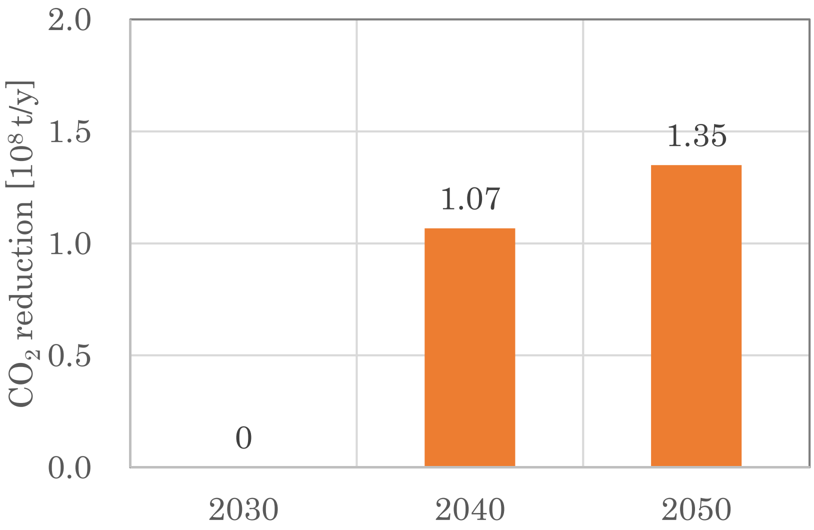


Fig.3-3 Amount of CO_2 reduction by hydrogen fired power plant

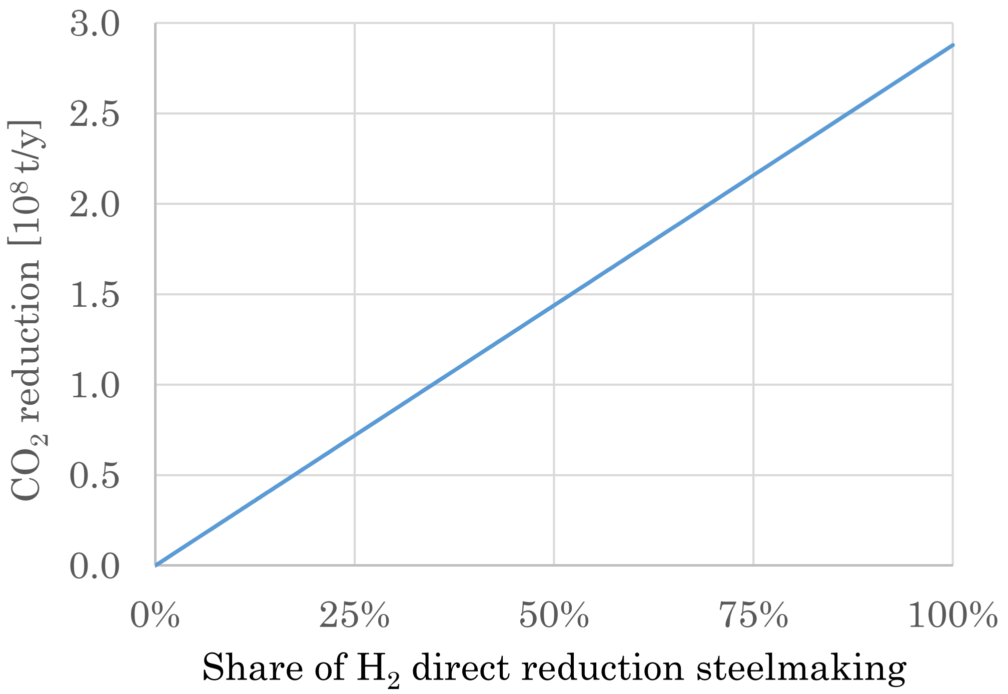
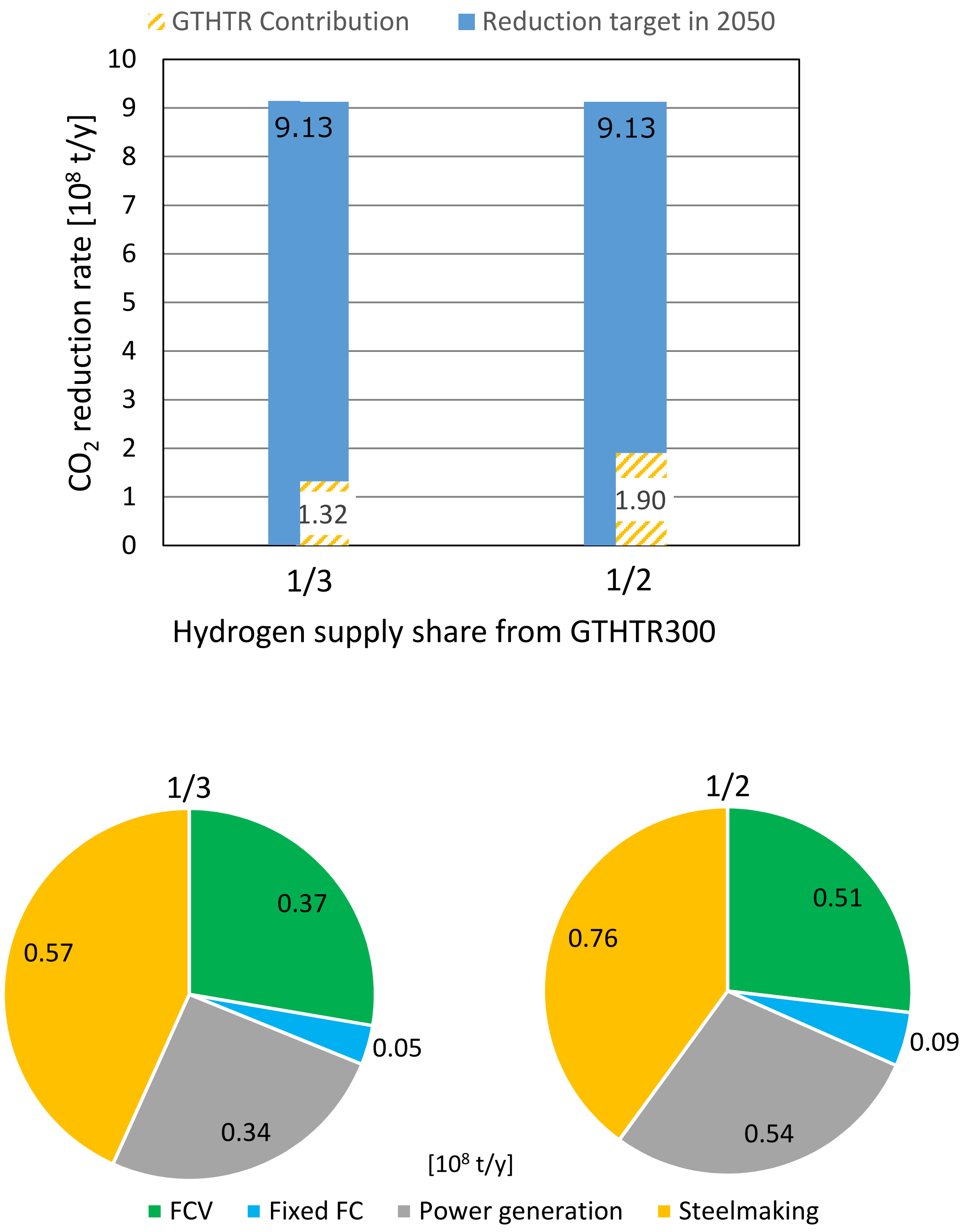


Fig.3-4 CO_2 reduction as a function of share of hydrogen direct reduction steelmaking



Contribution of GTHTR300

Fig.3-5 Contribution of CO_2 reduction by GTHTR300 hydrogen production

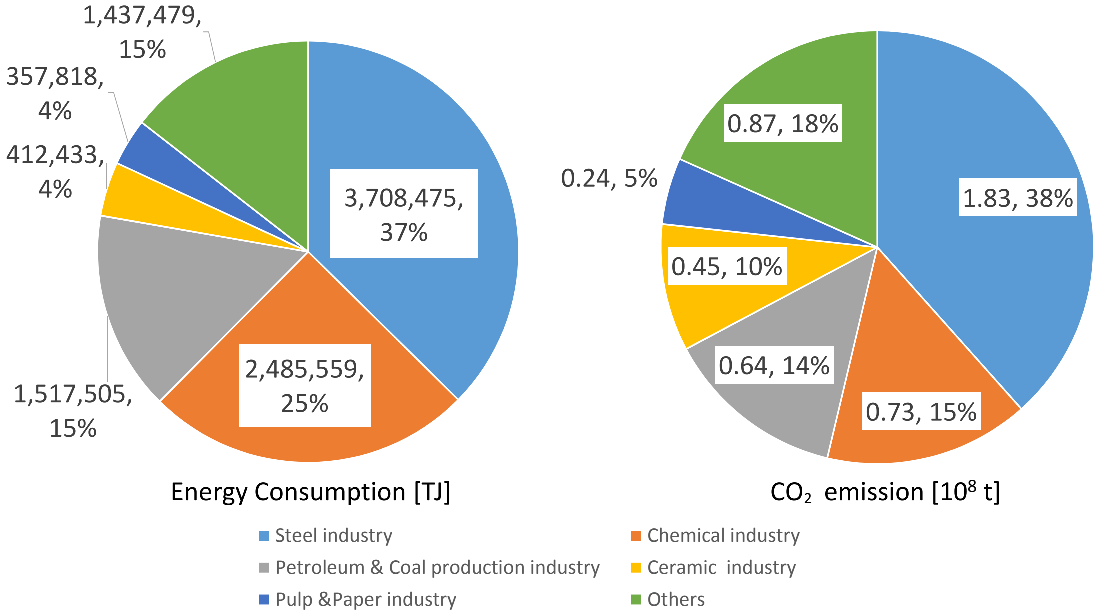


Fig.3-6 Energy consumption and CO_2 emission in industry sector in 2013

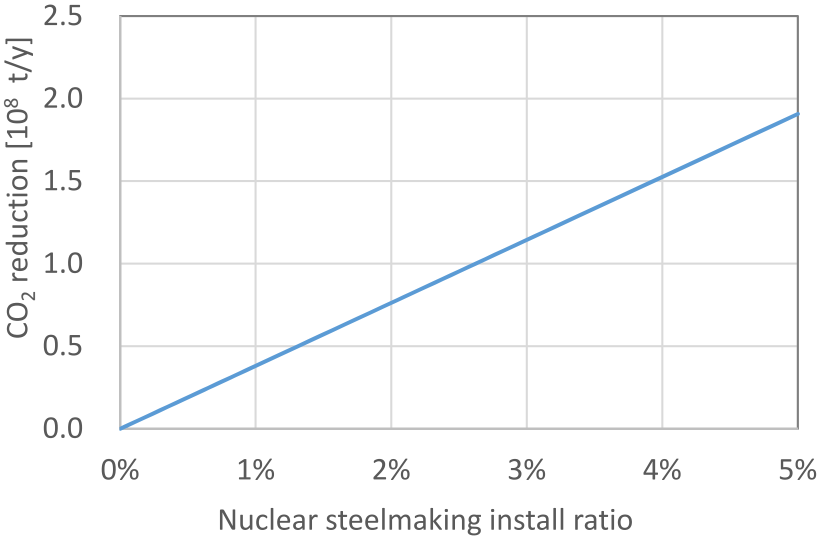


Fig. 4-1 World CO_2 reduction rate (w/o Japan) by nuclear energy steelmaking in 2050

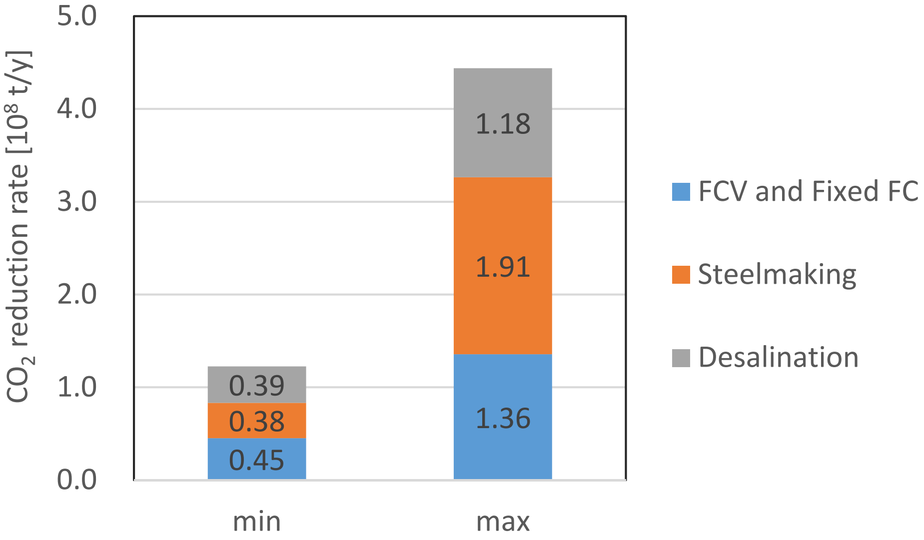


Fig. 4-2 Contribution of CO$_2$ reduction by GTHTR300 overseas deployment

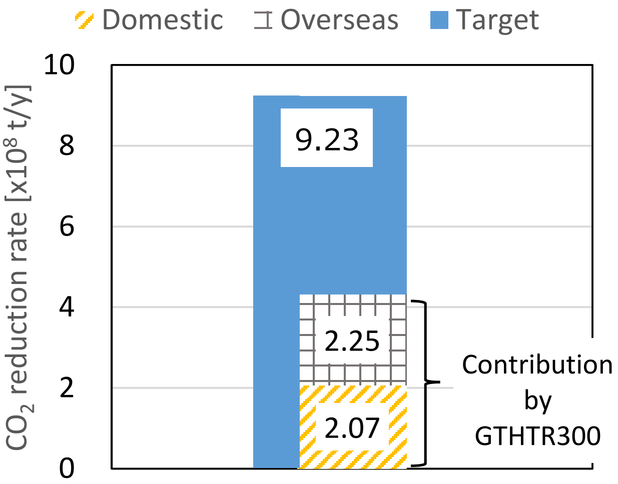


Fig. 5-1 The best estimate of HTGR contribution to Japan’s CO$_2$ emission reduction goal in 2050

国際単位系（SI）

表１．SI 基本単位

基本量	SI 基本単位	
	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd

表２．基本単位を用いて表されるSI組立単位の例

組立量	SI 組立単位	
	名称	記号
面積	平方メートル	m^2
体積	立方メートル	m^3
速さ，速度	メートル毎秒	m/s
加速度	メートル毎秒毎秒	m/s^2
波数	毎メートル	m^{-1}
密度，質量密度	キログラム毎立方メートル	kg/m^3
面積密度	キログラム毎平方メートル	kg/m^2
比体積	立方メートル毎キログラム	m^3/kg
電流密度	アンペア毎平方メートル	A/m^2
磁界の強さ	アンペア毎メートル	A/m
量濃度(a)，濃度	モル毎立方メートル	mol/m^3
質量濃度	キログラム毎立方メートル	kg/m^3
輝度	カンデラ毎平方メートル	cd/m^2
屈折率(b)	（数字の） 1	1
比透磁率(b)	（数字の） 1	1

(a) 量濃度（amount concentration）は臨床化学の分野では物質濃度（substance concentration）ともよばれる。

(b) これらは無次元量あるいは次元１をもつ量であるが、そのことを表す単位記号である数字の１は通常は表記しない。

表３．固有の名称と記号で表されるSI組立単位

組立量	SI 組立単位			
	名称	記号	他のSI単位による表し方	SI基本単位による表し方
平面角	ラジアン(b)	rad	1 (b)	m/m
立体角	ステラジアン(b)	sr(c)	1 (b)	m^2/m^2
周波数	ヘルツ(d)	Hz		s^{-1}
力	ニュートン	N		$m\ kg\ s^{-2}$
圧力，応力	パスカル	Pa	N/m^2	$m^{-1}\ kg\ s^{-2}$
エネルギー，仕事，熱量	ジュール	J	N m	$m^2\ kg\ s^{-2}$
仕事率，工率，放射束	ワット	W	J/s	$m^2\ kg\ s^{-3}$
電荷，電気量	クーロン	C		s A
電位差（電圧），起電力	ボルト	V	W/A	$m^2\ kg\ s^{-3}\ A^{-1}$
静電容量	ファラド	F	C/V	$m^{-2}\ kg^{-1}\ s^4\ A^2$
電気抵抗	オーム	Ω	V/A	$m^2\ kg\ s^{-3}\ A^{-2}$
コンダクタンス	ジーメンス	S	A/V	$m^{-2}\ kg^{-1}\ s^3\ A^2$
磁束	ウエーバ	Wb	Vs	$m^2\ kg\ s^{-2}\ A^{-1}$
磁束密度	テスラ	T	Wb/m^2	$kg\ s^{-2}\ A^{-1}$
インダクタンス	ヘンリー	H	Wb/A	$m^2\ kg\ s^{-2}\ A^{-2}$
セルシウス温度	セルシウス度(e)	℃		K
光束	ルーメン	lm	cd sr(c)	cd
照度	ルクス	lx	lm/m^2	$m^{-2}\ cd$
放射性核種の放射能(f)	ベクレル(d)	Bq		s^{-1}
吸収線量, 比エネルギー分与, カーマ	グレイ	Gy	J/kg	$m^2\ s^{-2}$
線量当量, 周辺線量当量, 方向性線量当量, 個人線量当量	シーベルト(g)	Sv	J/kg	$m^2\ s^{-2}$
酸素活性	カタール	kat		$s^{-1}\ mol$

(a)SI接頭語は固有の名称と記号を持つ組立単位と組み合わせても使用できる。しかし接頭語を付した単位はもはやコヒーレントではない。

(b)ラジアンとステラジアンは数字の１に対する単位の特別な名称で、量についての情報をつたえるために使われる。実際には、使用する時には記号rad及びsrが用いられるが、習慣として組立単位としての記号である数字の１は明示されない。

(c)測光学ではステラジアンという名称と記号srを単位の表し方の中に、そのまま維持している。

(d)ヘルツは周期現象についてのみ、ベクレルは放射性核種の統計的過程についてのみ使用される。

(e)セルシウス度はケルビンの特別な名称で、セルシウス温度を表すために使用される。セルシウス度とケルビンの単位の大きさは同一である。したがって、温度差や温度間隔を表す数値はどちらの単位で表しても同じである。

(f)放射性核種の放射能（activity referred to a radionuclide）は、しばしば誤った用語で"radioactivity"と記される。

(g)単位シーベルト（PV,2002,70,205）についてはCIPM勧告2（CI-2002）を参照。

表４．単位の中に固有の名称と記号を含むSI組立単位の例

組立量	SI 組立単位		
	名称	記号	SI 基本単位による表し方
粘度	パスカル秒	Pa s	$m^{-1}\ kg\ s^{-1}$
力のモーメント	ニュートンメートル	N m	$m^2\ kg\ s^{-2}$
表面張力	ニュートン毎メートル	N/m	$kg\ s^{-2}$
角速度	ラジアン毎秒	rad/s	$m\ m^{-1}\ s^{-1}=s^{-1}$
角加速度	ラジアン毎秒毎秒	rad/s^2	$m\ m^{-1}\ s^{-2}=s^{-2}$
熱流密度，放射照度	ワット毎平方メートル	W/m^2	$kg\ s^{-3}$
熱容量，エントロピー	ジュール毎ケルビン	J/K	$m^2\ kg\ s^{-2}\ K^{-1}$
比熱容量，比エントロピー	ジュール毎キログラム毎ケルビン	J/(kg K)	$m^2\ s^{-2}\ K^{-1}$
比エネルギー	ジュール毎キログラム	J/kg	$m^2\ s^{-2}$
熱伝導率	ワット毎メートル毎ケルビン	W/(m K)	$m\ kg\ s^{-3}\ K^{-1}$
体積エネルギー	ジュール毎立方メートル	J/m^3	$m^{-1}\ kg\ s^{-2}$
電界の強さ	ボルト毎メートル	V/m	$m\ kg\ s^{-3}\ A^{-1}$
電荷密度	クーロン毎立方メートル	C/m^3	$m^{-3}\ s\ A$
表面電荷	クーロン毎平方メートル	C/m^2	$m^{-2}\ s\ A$
電束密度，電気変位	クーロン毎平方メートル	C/m^2	$m^{-2}\ s\ A$
誘電率	ファラド毎メートル	F/m	$m^{-3}\ kg^{-1}\ s^4\ A^2$
透磁率	ヘンリー毎メートル	H/m	$m\ kg\ s^{-2}\ A^{-2}$
モルエネルギー	ジュール毎モル	J/mol	$m^2\ kg\ s^{-2}\ mol^{-1}$
モルエントロピー, モル熱容量	ジュール毎モル毎ケルビン	J/(mol K)	$m^2\ kg\ s^{-2}\ K^{-1}\ mol^{-1}$
照射線量（Ｘ線及びγ線）	クーロン毎キログラム	C/kg	$kg^{-1}\ s\ A$
吸収線量率	グレイ毎秒	Gy/s	$m^2\ s^{-3}$
放射強度	ワット毎ステラジアン	W/sr	$m^4\ m^{-2}\ kg\ s^{-3}=m^2\ kg\ s^{-3}$
放射輝度	ワット毎平方メートル毎ステラジアン	$W/(m^2\ sr)$	$m^2\ m^{-2}\ kg\ s^{-3}=kg\ s^{-3}$
酵素活性濃度	カタール毎立方メートル	kat/m^3	$m^{-3}\ s^{-1}\ mol$

表５．SI 接頭語

乗数	名称	記号	乗数	名称	記号
10^{24}	ヨタ	Y	10^{-1}	デシ	d
10^{21}	ゼタ	Z	10^{-2}	センチ	c
10^{18}	エクサ	E	10^{-3}	ミリ	m
10^{15}	ペタ	P	10^{-6}	マイクロ	µ
10^{12}	テラ	T	10^{-9}	ナノ	n
10^{9}	ギガ	G	10^{-12}	ピコ	p
10^{6}	メガ	M	10^{-15}	フェムト	f
10^{3}	キロ	k	10^{-18}	アト	a
10^{2}	ヘクト	h	10^{-21}	ゼプト	z
10^{1}	デカ	da	10^{-24}	ヨクト	y

表６．SIに属さないが、SIと併用される単位

名称	記号	SI 単位による値
分	min	1 min=60 s
時	h	1 h =60 min=3600 s
日	d	1 d=24 h=86 400 s
度	°	1°=(π/180) rad
分	’	1’=(1/60)°=(π/10 800) rad
秒	”	1”=(1/60)’=(π/648 000) rad
ヘクタール	ha	1 ha=1 $hm^2=10^4m^2$
リットル	L，l	1 L=1 l=1 $dm^3=10^3cm^3=10^{-3}m^3$
トン	t	1 $t=10^3$ kg

表７．SIに属さないが、SIと併用される単位で、SI単位で表される数値が実験的に得られるもの

名称	記号	SI 単位で表される数値
電子ボルト	eV	1 eV=1.602 176 53(14)$\times10^{-19}$J
ダルトン	Da	1 Da=1.660 538 86(28)$\times10^{-27}$kg
統一原子質量単位	u	1 u=1 Da
天文単位	ua	1 ua=1.495 978 706 91(6)$\times10^{11}$m

表８．SIに属さないが、SIと併用されるその他の単位

名称	記号	SI 単位で表される数値
バール	bar	1 bar=0.1MPa=100 kPa=10^5Pa
水銀柱ミリメートル	mmHg	1 mmHg≈133.322Pa
オングストローム	Å	1 Å=0.1nm=100pm=10^{-10}m
海里	M	1 M=1852m
バーン	b	1 b=100$fm^2=(10^{-12}cm)^2=10^{-28}m^2$
ノット	kn	1 kn=(1852/3600)m/s
ネーパ	Np	SI単位との数値的な関係は、対数量の定義に依存。
ベル	B	
デシベル	dB	

表９．固有の名称をもつCGS組立単位

名称	記号	SI 単位で表される数値
エルグ	erg	1 erg=10^{-7} J
ダイン	dyn	1 dyn=10^{-5}N
ポアズ	P	1 P=1 dyn s cm^{-2}=0.1Pa s
ストークス	St	1 St =1$cm^2\ s^{-1}=10^{-4}m^2\ s^{-1}$
スチルブ	sb	1 sb =1cd $cm^{-2}=10^4$cd m^{-2}
フォト	ph	1 ph=1cd sr cm^{-2} =10^4lx
ガル	Gal	1 Gal =1cm $s^{-2}=10^{-2}ms^{-2}$
マクスウエル	Mx	1 Mx = 1G $cm^2=10^{-8}$Wb
ガウス	G	1 G =1Mx cm^{-2} =10^{-4}T
エルステッド(a)	Oe	1 Oe ≙ $(10^3/4\pi)$A m^{-1}

(a) ３元系のCGS単位系とSIでは直接比較できないため、等号「 ≙ 」は対応関係を示すものである。

表10．SIに属さないその他の単位の例

名称	記号	SI 単位で表される数値
キュリー	Ci	1 Ci=3.7$\times10^{10}$Bq
レントゲン	R	1 R = 2.58$\times10^{-4}$C/kg
ラド	rad	1 rad=1cGy=10^{-2}Gy
レム	rem	1 rem=1 cSv=10^{-2}Sv
ガンマ	γ	1 γ =1 nT=10^{-9}T
フェルミ		1 フェルミ=1 fm=10^{-15}m
メートル系カラット		1 メートル系カラット= 0.2 g = 2$\times10^{-4}$kg
トル	Torr	1 Torr = (101 325/760) Pa
標準大気圧	atm	1 atm = 101 325 Pa
カロリー	cal	1 cal=4.1858J（「15℃」カロリー），4.1868J（「IT」カロリー），4.184J（「熱化学」カロリー）
ミクロン	µ	1 µ =1µm=10^{-6}m

（第8版，2006年）