Journal of Nuclear Materials 398 (2010) 1–9

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

Role of nuclear energy to a future society of shortage of energy resources and global warming

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ABSTRACT

Human society entered into the society of large energy consumption since the industrial revolution and consumes more than 10 billion tons of oil equivalent energy a year in the world in the present time, in which over 80% is provided by fossil fuels such as coal, oil and natural gas. Total energy consumption is foreseen to increase year by year from now on due to significant economical and population growth in the developing countries such as China and India. However, fossil fuel resources are limited with conventional crude oil estimated to last about 40 years, and it is said that the peak oil production time has come now. On the other hand, global warming due to green house gases (GHG) emissions, especially carbon dioxide, has become a serious issue.

Nuclear energy plays an important role as means to resolve energy security and global warming issues. Four hundred twenty-nine nuclear power plants are operating world widely producing 16% of the total electric power with total plant capacity of 386 GWe without emission of CO_2 as of 2006. It is estimated that another 250 GWe nuclear power is needed to keep the same level contribution of electricity generation in 2030. On the other hand, the Japan Atomic Energy Research Institute (JAERI) developed the very high temperature gas-cooled reactor (HTGR) named high temperature gas-cooled engineering test reactor (HTTR) and carbon free hydrogen production process (IS process). Nuclear energy utilization will surely widen in, not only electricity generation, but also various industries such as steel making, chemical industries, together with hydrogen production for transportation by introduction of HTGRs. The details of development of the HTTR and IS process are also described.

1. Introduction

More than 10 billion tons of oil equivalent energy are consumed a year in the world in the present time and over 80% of it is provided by fossil fuels such as coal, oil and natural gas. Many specialists, institutes, international agencies and organizations have foreseen or estimated an increase of energy consumption in future, remaining fossil fuel resources, and the period of consumption of them.

On the other hand, global warming due to green house gases (GHG) emissions, especially carbon dioxide (CO_2) emitted by burning of fossil fuels has become a serious issue. The IPCC (Inter-governmental Panel on Climate Change) opened their Fourth Assessment Report [1] to the public last year indicating that anthropogenic warming over the last three decades has likely had a discernible influence at the global scale on observed changes in many physical and biological systems. The report also describes that altered frequencies and intensities of extreme weather, together with sea level rise, are expected to have mostly adverse effects on natural and human systems.

The G8 Summit leaders confirmed the significance of the Fourth Assessment Report of the IPCC as providing the most comprehensive assessment of the science and encouraged the continuation of the science-based approach that should guide our climate protection efforts in the G8 Hokkaido Toyako Summit Leaders Declaration. They also committed to avoiding the most serious consequences of climate change and determined to achieve the stabilization of atmospheric concentrations of global greenhouse gases considering and adopting the goal of achieving at least 50% reduction of global emissions by 2050.

Various considerations and measures to mitigation of climate change are expected in various sectors such as energy supply, transport and its infrastructure, residential and commercial buildings, industry, agriculture, forestry and waste management. Nuclear energy is an essential instrument of energy supply to mitigate global warming from the viewpoints of stable supply with necessary amounts, harmonization with global environment and economical competitiveness. The present status and perspective of electricity generation by nuclear power are discussed, covering that growing number of countries have recently expressed their

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doi:10.1016/j.jnucmat.2009.10.002

interests in nuclear power programs as means to resolve climate change and energy security issues. Furthermore, nuclear energy can also produce high temperature gas to be used as process heat in chemical industries and production of hydrogen which can be used for steel making, fuel cell vehicles and so on. The JAERI (currently JAEA) developed an HTGR to provide high temperature gas and succeeded in getting helium gas of 950 °C at the reactor outlet in the HTTR through the development of various materials and introduction of new design concepts. On the other hand, the JAERI developed a carbon free hydrogen production process in which the high temperature process heat can be provided by an HTGR. The process is high temperature thermo-chemical water splitting method using iodine and sulfur (IS process). Continuous efforts have been made to achieve continuous hydrogen production improving reaction conditions and developing materials.

2. Present situation and perspective of energy consumption

The total energy consumption in the world depends strongly on population. The current world population is 6.46 billion [2] as shown in Fig. 1. Two countries, China and India, hold more than one third of world population. The population in the developing countries is projected to increase enormously and reach to 8 billion, although population in the developed countries will be rather stable, slightly over 1 billion in 2050. Fig. 2 shows distribution of primary energy consumption by country [3]. The total amount of energy consumption in the world is 11.4 billion tons of oil equivalents in the present time. The USA's share is 20%, China's is 15%, Russia's is 6%, and India's is 5%, etc. The energy consumption per person for each country can be easily calculated from these two figures and it is shown for several developed and developing countries in Fig. 3. Canadian and American people consume around 8 tons of oil equivalent energy per year; that is 4.5 times higher than the global average. Most of European countries and Japan consume energy about a half of that of the former two countries. On the other hand, China and India consume energy one third and one eighth of the Europeans per person, respectively. That means, no developed country can request that the developing countries should not consume much more energy than the present amount, or complain that they consume more energy, because people in these countries have the right to consume energy and improve their living standards as same level as those of the developed countries.

Fig. 4 shows past and future consumption of various energy sources from 1970 to 2030 evaluated by OECD/IEA [4]. The Agency estimated further increase of consumption of fossil fuels and that the total amount of energy consumption in 2030 will become 1.6 times higher than that in the present time. The IIASA-WEC's projection of energy consumption by several regions for much longer time span [5] is shown in Fig. 5. The total amount of energy con-

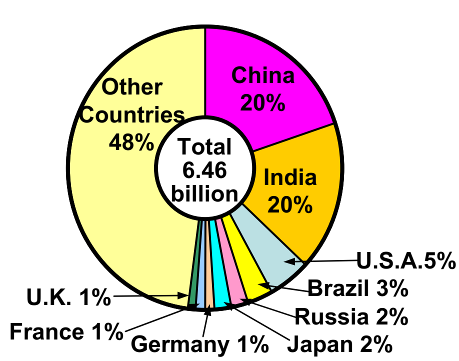

Fig. 1. Distribution of population by country (2005).

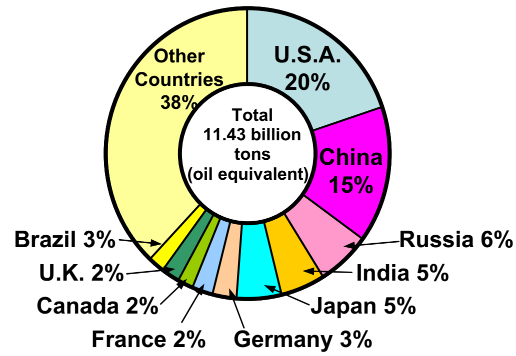

Fig. 2. Distribution of primary energy consumption by country (2005).

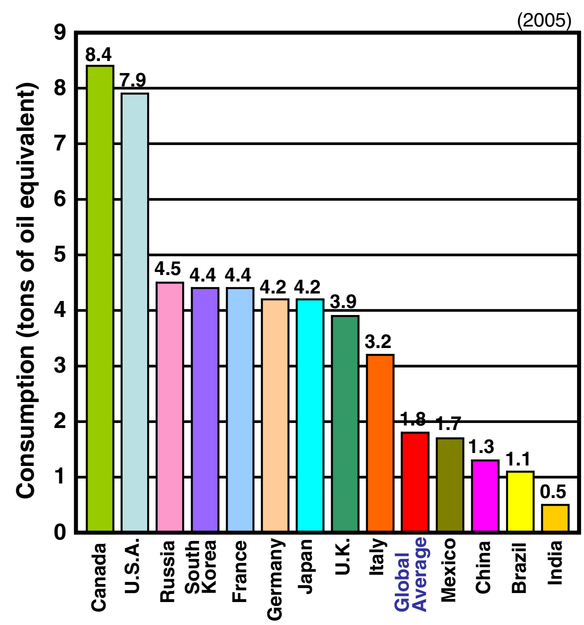

Fig. 3. Energy consumption by capita.

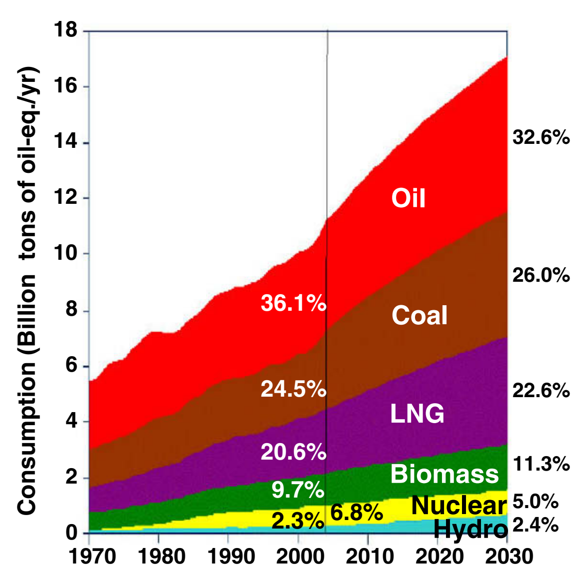

Fig. 4. History and perspective of world energy consumption by energy sources.

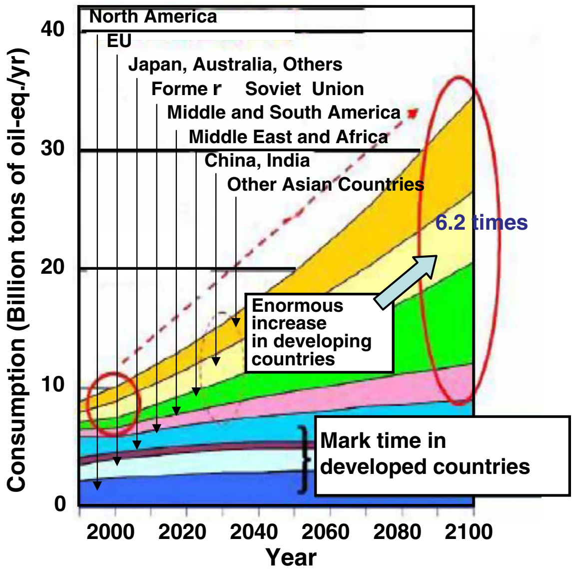

Fig. 5. History and perspective of world energy consumption by region.

sumption in the developing countries will exceed that in the developed countries in 2030, and will continue to increase dramatically. The total amount of energy consumption in 2100 will reach to 6.2 times of that in 2000 in the developing countries. This leads to the obvious question: are there so many energy resources in the earth?

The British Petroleum evaluated energy resource reserves and reserve–production ratio for fossil fuels [6] and IAEA and OECD/NEA projected them for uranium [7], as shown in Fig. 6. The reserve–production ratios of oil and natural gas are only 40 and 60 years, respectively. The definition of reserve–production ratio, here, is the reserve remaining at the end of year per production in that year. So, as far as new energy resources are not discovered and production is constant, the reserve–production ratio decreases 1 year for each energy source every year. If production in some year increases much more, the reserve–production ratio decreases much rapidly. As concerns uranium resources, the reserve is 5.47 million tons and the reserve-production ratio is more than 100 years. Furthermore, it becomes over 3000 years if a Fast Breeder Reactor (FBR) which produces more new plutonium fuel than spent plutonium becomes commercial. Namely, utilization efficiency of uranium resources reaches about 60% in the FBR cycle due to breeding plutonium fuel from uranium, recycling plutonium fuel and un-necessity of uranium enrichment with loss of uranium resources although it is about 0.5% in once-through use of uranium in a light water reactor. The reserve–production ratio sets here conservatively 30 times larger than that of once-through use case considering loss of recycling plutonium and uranium in the processes of re-processing of spent fuels and fuel fabrication.

The amount of oil resources is a keen issue. Fig. 7 shows the history of the total amount of oil of newly discovered oil fields. Most large oil fields were discovered between 1950 and 1960s, and discovery of new oil fields has stagnated since 1980 and is foreseen to decline sharply [8]. Many specialists in this field say that peak production of oil has already happened, and Japan Oil Association also predicts that peak oil production happens in 2009. It seems apparent that the global production of conventional oil will begin to decline soon and the time of cheap oil will end. A period of consumption of oil is just a moment if time span is described in linear scale as shown in Fig. 8. We consume all of oil resource within 200 years, which was formed in the dinosaurian time of 200–60 million years ago.

3. Global warming due to emissions of green house gases

Global warming due to green house gases (GHG), especially carbon dioxide (CO_2) emission has become a serious issue. Carbon dioxide emissions by burning of fossil fuels scarcely occurred before the industrial revolution and atmospheric carbon dioxide concentration was stable at about 280 ppm. CO_2 emissions have increased at first as the amount of coal consumption increased after the revolution, and then again after World War II together with oil consumption with industrial progress and economical expansion in developed countries. Recently, CO_2 emissions due to burning of natural gas have been added. An increase of CO_2 emissions in the last 35–40 years has been substantial and the total amount of CO_2 emissions due to burning of fossil fuels reaches to about 26 billion tons. In accordance to this tendency, CO_2 concentration in the atmosphere has increased from 280 ppm before the industrial revolution to about 380 ppm in the present time.

The IPCC reports that warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level [1]. Anthropo-

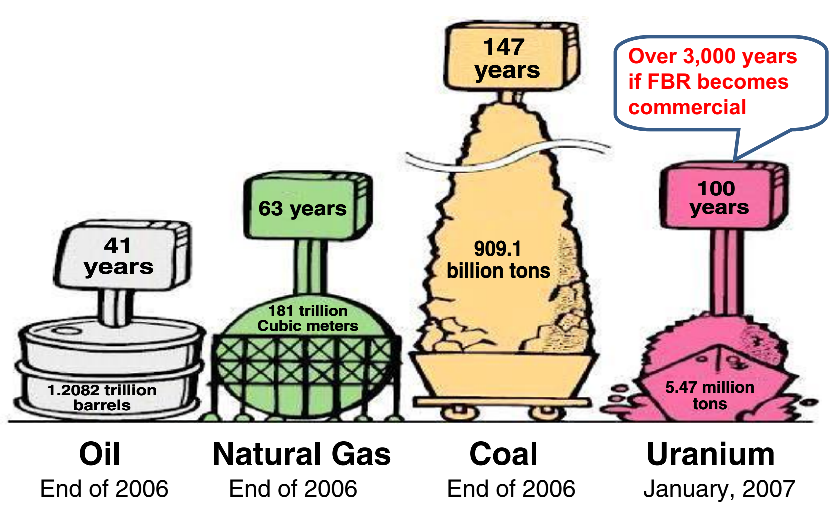

Fig. 6. Proved reserves of energy resources.

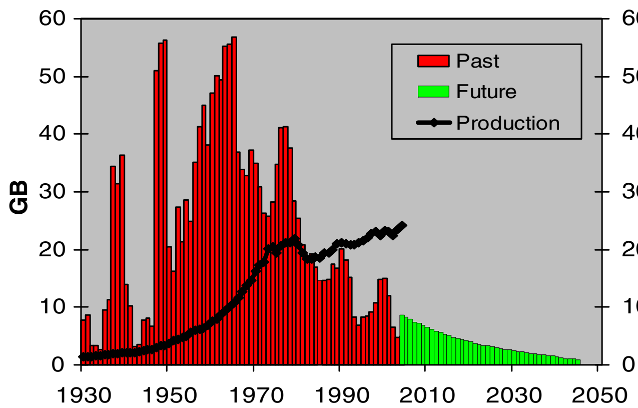

Fig. 7. Total discovery of new oil fields.

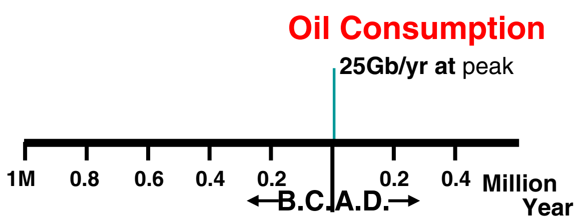

Fig. 8. Extremely short period of oil consumption.

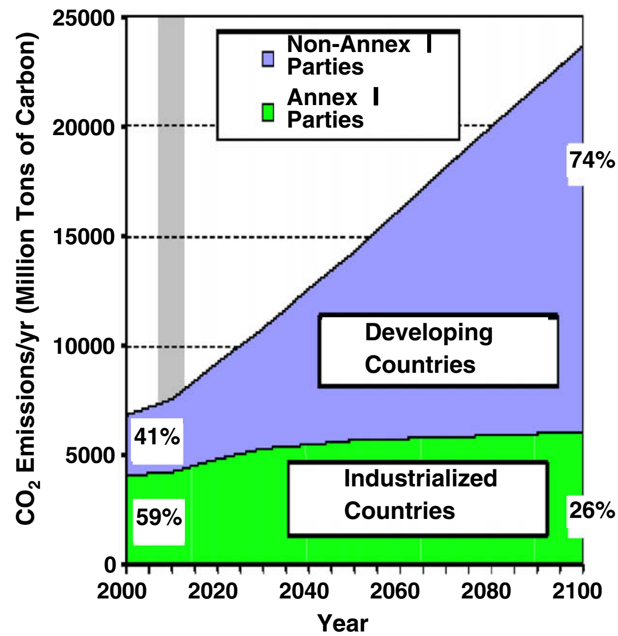

Fig. 10. Long range CO_2 emission outlook.

genic warming over the last three decades has likely had a discernible influence on the global scale on observed changes in many physical and biological systems.

How much will increase CO_2 emissions in future?

Several international organizations and institutes have projected CO_2 emissions. Fig. 9 shows CO_2 emissions per year by countries in 2004 and estimated ones in 2030 by IEA [4]. The total CO_2 emissions in the world per year will increase from 26 billion tons to more than 40 billion tons between 2004 and 2030, 1.6 times higher than the present CO_2 emissions. Every country and region will emit more amount of CO_2 per year. The IIASA, Institute of International Association on System Analysis estimated that CO_2 emissions per year in 2100 would reach 3.5 times higher than those in 2000 [5], mostly due to increase of CO_2 emissions in the developing countries as shown in Fig. 10.

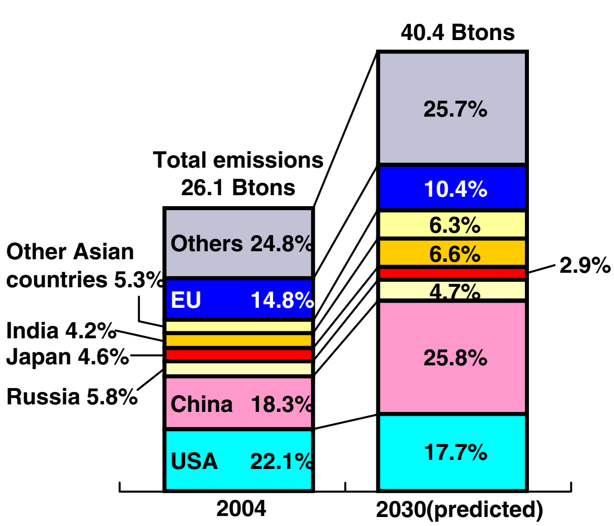

Fig. 9. Present status and outlook of CO_2 emissions/year by countries.

The IPCC suggested to policy makers to make a great effort to reduce CO_2 emissions providing six characteristics of stabilization scenarios as shown in Table 1. In order to stabilize the concentration of GHGs in the atmosphere, emissions would need to peak and decline thereafter. The lower the stabilization level is, the more quickly this peak and decline would need to occur. Mitigation efforts over the next 2–3 decades will have a large impact on opportunities to achieve lower stabilization levels. In order to achieve less impact on global physical and biological systems, the temperature increase should be maintained within 2 °C, that is category I in the table, namely, we have to reduce CO_2 emissions in 2050 by 50–85% of those in 2000 together with establishment of peaking year of CO_2 emissions by 2015. The G8 Summit leaders committed to avoiding the most serious consequences of climate change and determined to achieve the stabilization of atmospheric concentrations of global greenhouse gases considering and adopting the goal of achieving at least 50% reduction of global emissions by 2050 [9].

4. Current and future role of nuclear energy

4.1. Electricity generation

Although nuclear energy has a misfortune and tragic history to be used first as nuclear bomb, peaceful use of nuclear energy was initiated and has been promoted based on the speech of "Atoms for Peace" by USA President Eisenhower at United Nations in 1953. Many developed countries started and promoted the construction of nuclear power plants mostly due to oil crises and energy security. However, the pace of construction of nuclear power plants became stagnant in several countries after Three Mile Island (TMI) and Chernobyl accidents. Currently, 429 nuclear power plants are operating world-wide, producing 16% of the total electricity generation, or 6% of all primary energy production with total plant capacity of 387 GWe [10] as shown in Fig. 11. USA has a quarter of the total producing 20% of the total electricity generation in the country, nuclear power produces 80% of the total electricity generation which reaches to truly 43% of primary energy production in France and one third of the total, or 14% of all primary energy production in Japan.

Table 1
Characteristics of stabilization scenarios and resulting long-term equilibrium global average temperature and sea level rises (IPCC fourth report).

Category		I	II	III	IV	V	VI
CO_2 concentration at stabilization (2005 = 379 ppm)	ppm	350–400	400–440	440–485	485–570	570–660	660–790
CO_2-equivalent Concentration at stabilization including GHGs and aerosols (2005 = 375 ppm)	ppm	445–490	490–535	535–590	590–710	710–855	855–1130
Peaking year for CO_2 emissions	Year	2000–2015	2000–2020	2010–2030	2020–2060	2050–2080	2060–2090
Change in global CO_2 emissions in 2050 from 2000	%	−85 to −50	−60 to −30	−30 to +5	+10 to +60	+25 to +85	+90 to +140
Global average temperature increase above pre-industrial at equilibrium, using "best estimate" climate sensitivity	°C	2.0–2.4	2.4–2.8	2.8–3.2	3.2–4.0	4.0–4.9	4.9–6.1
Global average sea level rise above pre-industrial at equilibrium from thermal expansion only	m	0.4–1.4	0.5–1.7	0.6–1.9	0.6–2.4	0.8–2.9	1.0–3.7
Number of assessed scenarios		6	18	21	118	9	5

Atmospheric CO_2 concentrations were 379 ppm in 2005. The best estimate of total CO_2-eq concentration in 2005 for all long-lived GHGs is about 455 ppm, while the corresponding value including the net effect of all anthropogenic forcing agents is 375 ppm CO_2-eq.

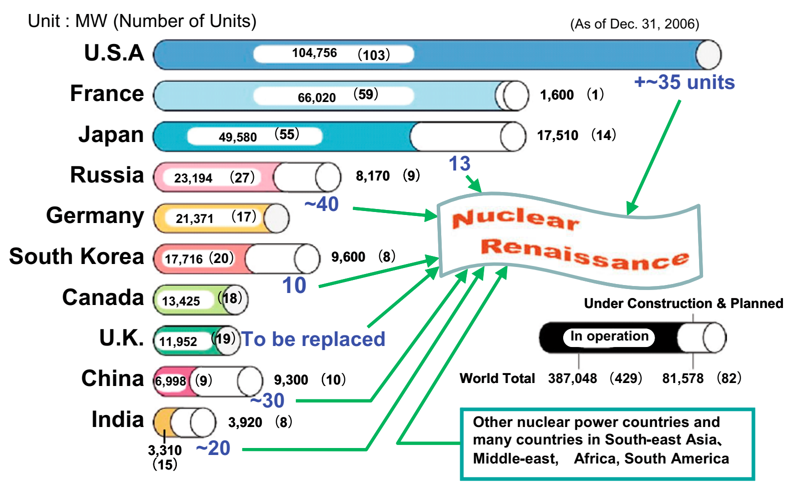

Fig. 11. Present status and perspective of nuclear power in major countries.

As described in the G8 Summit leaders declaration, a growing number of countries currently regard nuclear power as an essential instrument in reducing dependence on fossil fuels, and hence greenhouse gas emissions. Fig. 12 shows amount of CO_2 emissions through life cycle of each electricity energy source in unit of g-CO_2 per kWeh [11]. Clearly, fossil fuel fired power plants emit enormous amounts of CO_2 from about 500 g–1 kg/kWeh compared with renewable energies and nuclear power which emit CO_2 only from 10 to 50 g/kWeh. In fact, amount of CO_2 emission by nuclear power is 1/25–1/45 of that by fossil fuel. If the existing nuclear

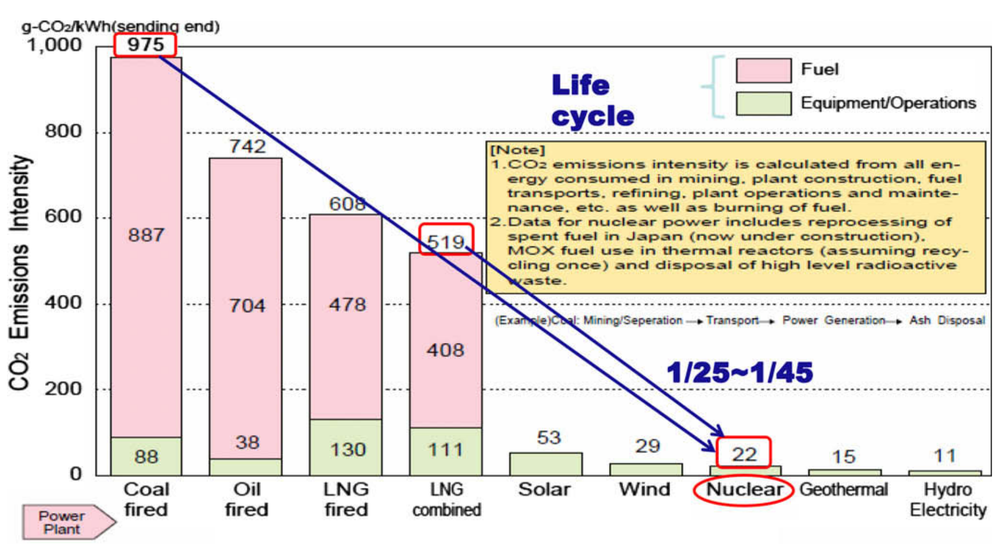

Fig. 12. CO_2 emissions intensity by electric source.

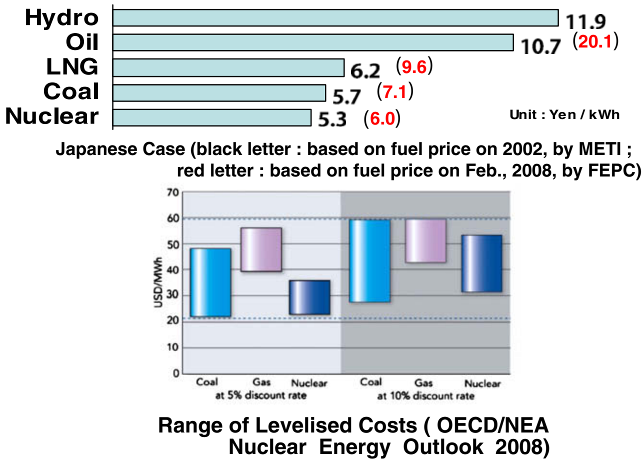

Fig. 13. Comparison of electricity generation cost.

Table 2
Reduction of CO_2 in 2030 from nuclear power generation (increase of energy consumption: 60%).

	Present	2030
Capacity	~400 GWe	
Share of total electricity	16%	+250 GWe (to maintain same share)
Contribution to CO_2 reduction	9%	
Contribution to CO_2 reduction by 20% (as same as in Japan)		+700 GWe

power plants are replaced with oil and coal fired power plants, for example, amount of CO_2 emissions would increase by 230 million tons, which is equivalent to about 20% of the total CO_2 emissions in Japan. Furthermore, nuclear power is the cheapest electricity source at least in Japan and in a similar situation internationally as shown in Fig. 13.

A number of countries have recently expressed their interests in nuclear power programs as means to addressing climate change and energy security concerns based on the situation described above, so it is said that we are entering a "Nuclear Renaissance". In fact, USA is going to re-start construction of some 35 new nuclear power plants after the TMI accident, France and Japan are steadily constructing new nuclear plants. Russia, China and India have big plans to build 20–40 new nuclear plants by 2020 or 2030, and several plants are being constructed already as added in Fig. 11. A plant unit capacity of them is 1000–1600 MWe mostly. Many other countries in Asia, Middle East, Africa and South America are considering introduction of nuclear power.

On the other hand, an increase of world-wide energy consumption in 2030 is projected to be 60% over the present level. In order to maintain the current level contribution of nuclear power of 16% to the total electricity generation in the world, another 250 GWe nuclear power is needed by 2030 under the assumption of the same ratio of electric power contribution to the total energy consumption, besides replacing retired nuclear plants with new ones meantime. The current contribution of nuclear power to the reduction of CO_2 emissions is about 9% in the world. If we wish to raise this figure to 20% in 2030, new nuclear power plants with about 700 GWe are needed by 2030, that is, construction of 700 nuclear power plants with a capacity of 1000 MWe in the world. It might be rather difficult figure from various points of view. These are summarized in Table 2.

4.2. Nuclear heat utilization in various industries

Another type of nuclear energy system has a great possibility to contribute to create a low carbon future society together with current nuclear power system. That is a high temperature gas-cooled reactor, HTGR, which can produce helium gas of about 1000 °C at the reactor outlet. If so high temperature gas can be obtained, fields of nuclear energy utilization are surely widen in not only electricity generation but also hydrogen production, direct steel making by deoxidization of iron ore, process heat in various chemical industries, and so on, as shown in Fig. 14. That means also to contribute as countermeasure against shortage of oil, coal and natural gas. Currently, only two HTGR test reactors, namely, HTTR in Japan and HTR-10 in China, are operating in the world. The HTR-10 is a very small reactor and helium gas temperature at the reactor outlet is 700 °C. Furthermore, the technology of high temperature thermo-chemical decomposition of water utilizing iodine and sulfur has most progressed in the JAERI in the world. Therefore, the most advanced technologies in these fields in the JAERI are described here.

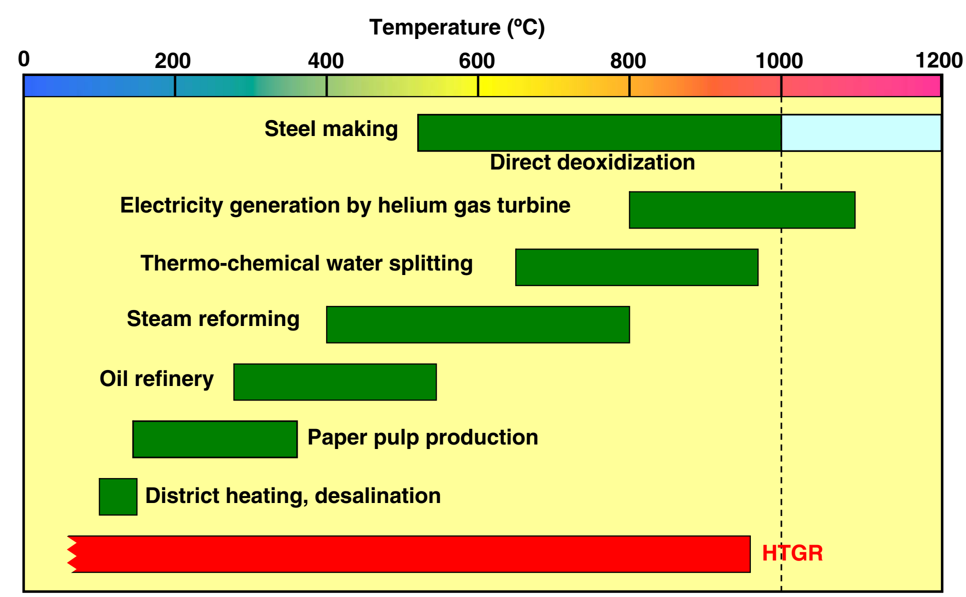

Fig. 14. Process heat temperature ranges used in various industries.

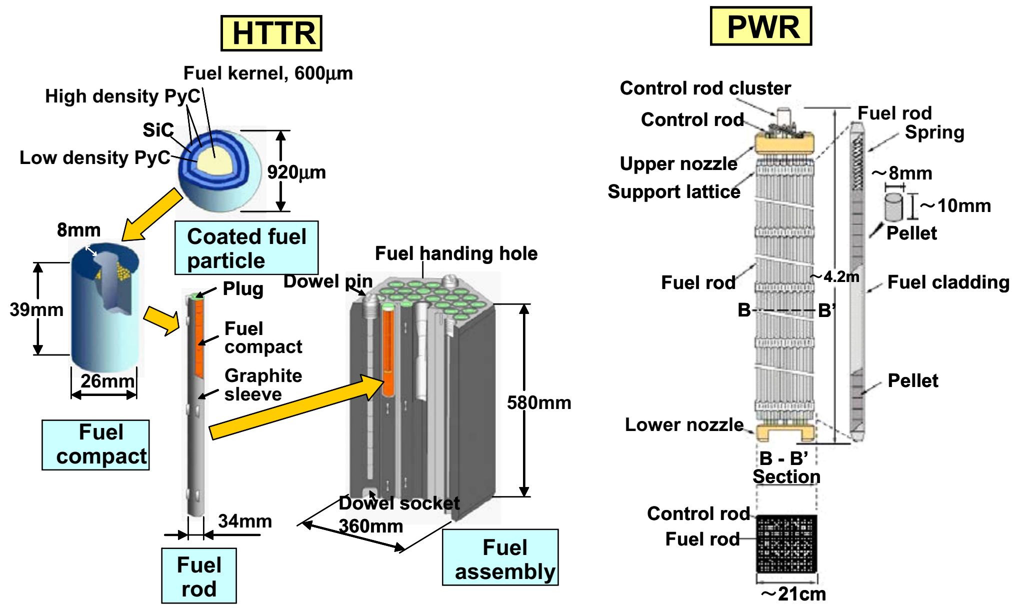

Fig. 15. Details of fuel structure of HTTR and LWR.

The JAERI developed the HTTR [12], a 30 MWt HTGR test reactor, and succeeded in getting helium gas of 950 °C at reactor outlet of the HTTR in 2004 for the first time in the world. Several key technologies are described below. One of big differences between an LWR and an HTGR is that no metal is used in the reactor core of the HTGR. The fuel element of HTTR, for example, is quite different from that of LWR as shown in Fig. 15. In the HTTR, coated fuel particles consisted of low enriched UO_2 kernel with TRISO coating are combined with graphite powder to form a fuel compact which is equivalent to UO_2 pellet in LWR. A fuel rod is composed of graphite sleeve in which fuel compacts are contained. A fuel assembly is a pin-in-block type hexagonal fuel element, that is, helium gas flows through the gap between a vertical hole and a fuel rod to remove the heat produced by fission and gamma heating. Excellent graphite for core and its surrounding components which has less dimensional change due to neutron irradiation, large tensile strength and high corrosion resistance is needed. The JAERI succeeded in development of IG-110 which satisfies the above-mentioned requirements as shown in Fig. 16. As concerns the coated fuel particle, great efforts had been made to improve fabrication technologies having made neutron irradiation tests resulting in production of very high quality one. As for heat resistant alloy for piping systems, Ni-base Hastelloy XR with very high corrosion resistance had been finally developed.

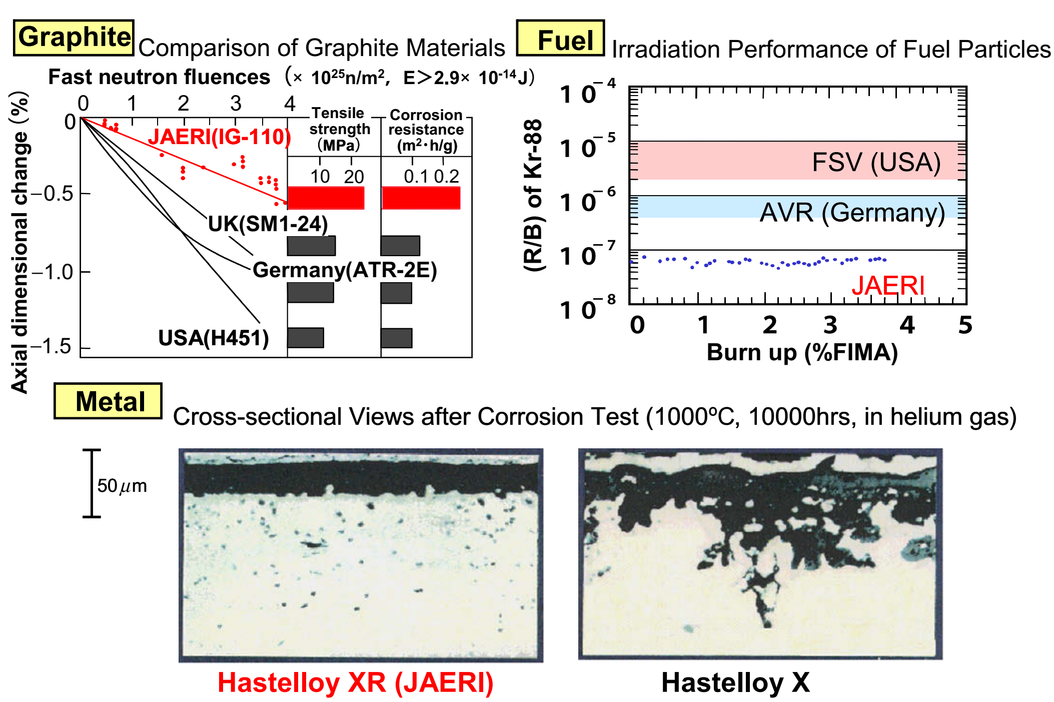

Fig. 16. Several results of research and development for HTTR.

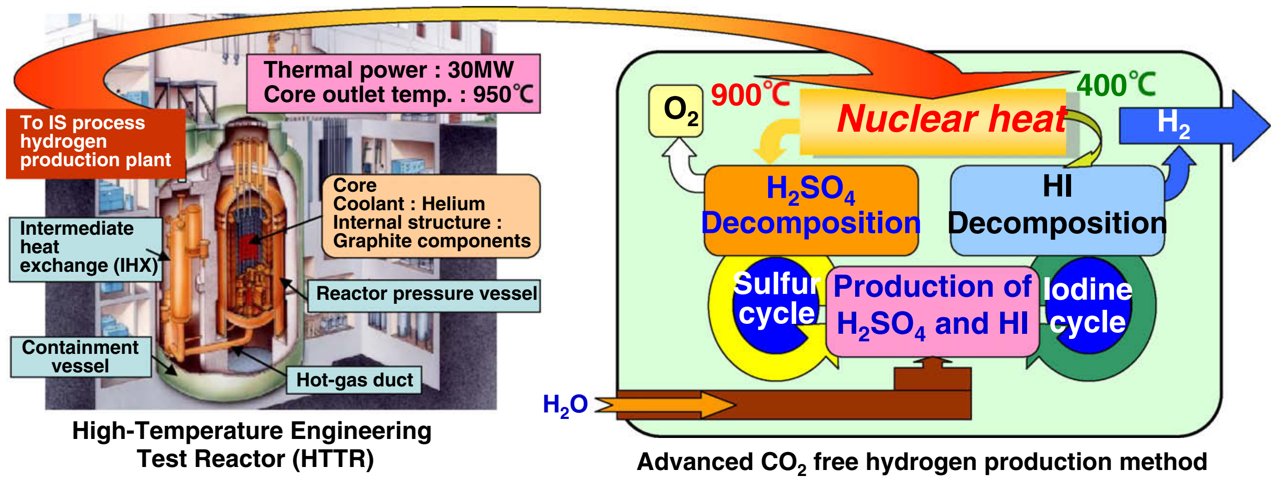

Fig. 17. Nuclear heat application from HTGR to IS-hydrogen production.

Hydrogen is said to be a 21st century's clean energy. However, if it is produced by utilizing fossil fuels as it was, such as in steam reforming process with CO_2 emissions, hydrogen is not really clean energy.

Therefore, the JAERI has devoted substantial resources to develop a high temperature thermo-chemical decomposition of water utilizing iodine and sulfur, the IS process as shown in Fig. 17 and successfully achieved continuous hydrogen production [13,14]. In this process, high temperature process heat is used in sulfuric acid and iodine hydride decomposition reactions. Iodine and sulfur are used cyclically, water is alone the feedstock to the hydrogen and oxygen as the only products. The IS process coupled with HTGR, Fig. 17, is a really clean hydrogen production system and economically competitive to those of steam reforming of methane and coal and superior to that of water electrolysis [15]. In fact, Ewan and Allen evaluated hydrogen cost for various production routes considered [16]. According to their report, hydrogen production costs per ton are 982 US$ for steam reforming of methane (SMR), 1575 US$ for SMR + carbon capture, 1270 US$ for nuclear/thermocycle, 1621 US$ for coal, 3114 US$ for coal + carbon capture, 4725 US$ for hydroelectric, 14,950 US$ for solar PV, etc. On the other hand, several methods are recently proposed to produce hydrogen utilizing an HTGR and other types of reactors [17–20], however, IS method is considered to be the most progressed, promising and good cost performance one without emission of CO_2 among them.

An HTGR with 600 MWt can produce 85,000 cubic meters of hydrogen per hour. Hydrogen can be used widely in fuel cell vehicles, fuel cell household, businesses, direct steel making, and industrial complex together with electricity generated by an HTGR, for example. A preliminary evaluation on the reduction of CO_2 emissions is made for the case in Japan [21]. A reduction of CO_2 of 170 million tons (13%) could be realized through the replacement of 50 million automobiles (2/3 of all cars in Japan) with fuel cell vehicles, 100 million tons (8%) by the adoption of direct steel making utilizing hydrogen and 30 million tons (2.3%) in the industrial complex by the adoption of process heat and electricity produced by an HTGR, respectively. Namely, a total amount of CO_2 reduction reaches to 23% of the total emission of 1.3 billion tons in Japan.

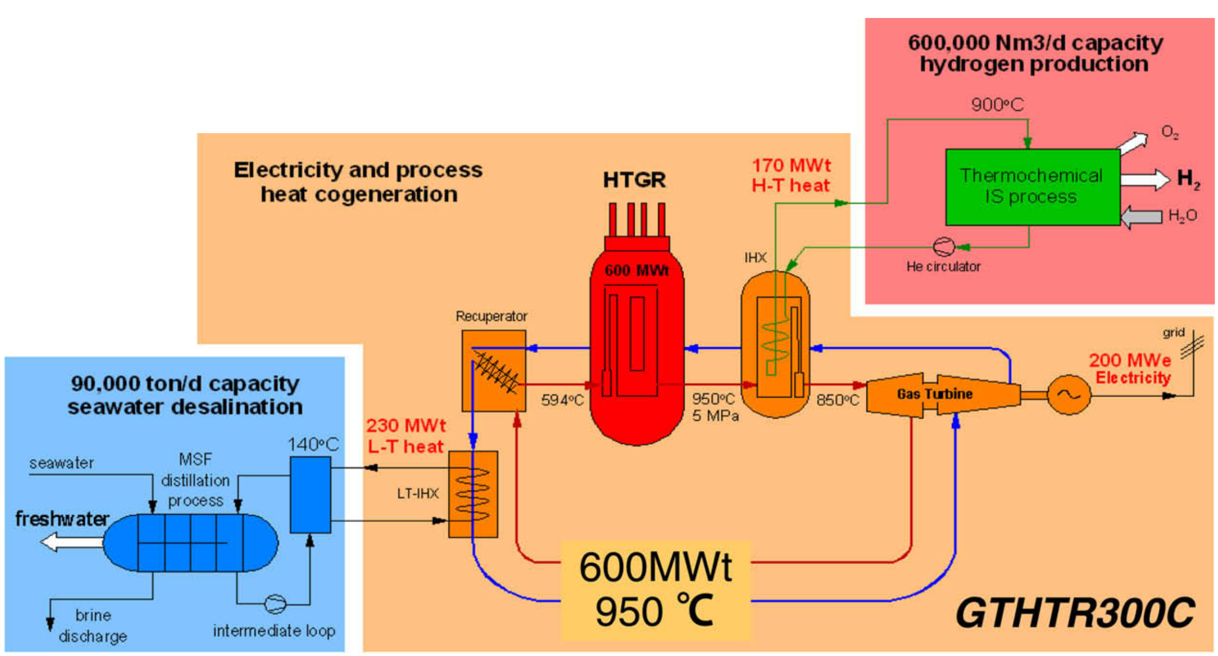

Fig. 18. HTGR cascade energy plant for 80% efficient production of hydrogen, electricity and freshwater.

As for spent fuel treatment and disposal, coated particle fuels are very convenient to direct disposal because fuel kernel is coated by ceramics triply. Re-processing of spent fuels is also possible by the current Purex method. Technologies of the pretreatment consisting of, in the case of prismatic fuel elements, separation of fuel particles from fuel compact and the following extraction of fuel kernel from a coated fuel particle by crashing have already been performed for HTTR fuels in a laboratory scale [15]. Concerning the chemical waste of the HTGR + IS, it will not bring a special issue to be considered since the IS process constitutes a closed cycle in terms of the sulfur- and iodine-compounds, in principle.

In addition, high temperature gas which can be obtained by an HTGR raises considerably total heat utilization efficiency up to 80% by utilizing heat in a cascade manner from high temperature to low temperature as shown in Fig. 18 [22], for example, although thermal efficiency of a current light water reactor (LWR) is 34%.

Commercialization of HTGR and HTGR–IS system could be attained through demonstration of HTTR–IS system and construction and operation of a demonstration HTGR with about 300 MWt.

Thus, HTGR technology combined with hydrogen production by the IS process applied world-wide would be expected to dramatically decrease global CO_2 emissions.

5. Conclusions

1. More than 10 billion tons of oil equivalent energy are consumed a year in the world in the present time, in which over 80% is provided by fossil fuels. Energy consumption is projected to increase by 60% in 2030 and by 240% in 2100, mostly in the developing countries despite a protected shortage of fossil fuels, especially oil and natural gas, within a few decades. On the other hand, consumption of large amounts of fossil fuels may have influenced global climate change. We will face the most serious consequences of climate change unless we stabilize the atmospheric concentrations of global greenhouse gases considering and adopting the goal of achieving at least 50% reduction of GHG emissions to the present figure by 2050.
2. Nuclear energy must play an essential role in reducing the dependence on fossil fuels and hence green house gas emissions, together with recognition of importance of renewable energy. Therefore, a growing number of countries have recently expressed their interests in nuclear power programs, so it is said that time is "Nuclear Renaissance". Nuclear energy can contribute as means to energy security and reduction of CO_2 emissions not only through electricity generation but also by heat application in various industries, hydrogen production available for transportation, steel making, for example. Commercialization of an HTGR that can produce heat of about 1000 °C based on the existing technologies will be vital to the realization of these goals.

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