Symbiotic energy demand and supply system based on collaboration between rare-earth and thorium utilization

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Abstract: Progressive economic growth as well as prodigious consumption of energy are expected among Asian countries. Nuclear power has myriad advantages, among them particularly being its status as a low carbon technology and therefore nuclear power would make a significant contribution to curtailing CO_2 emissions. However, the prospects for nuclear power are hindered by some unresolved problems: perceived adverse safety, environmental, and health effects; potential security risks stemming from proliferation; and unresolved challenges in long-term management of nuclear wastes. Thorium utilization as a nuclear fuel will serve as a cornerstone of circumventing such problems, because thorium produces less radioactive waste (*i.e.* less plutonium) and thus safety, which is of paramount concern, will be enhanced.

The deployment of electric vehicles (EVs) as an alternative to supplant gasoline engine cars in the transportation network, will significantly contribute in the reduction of global CO_2 emissions. Rare-earth materials such as neodymium and dysprosium will be essential as a new material for electric automobiles. Thorium is often obtained as a by-product of rare-earth metals, but it is still not utilized as a nuclear fuel currently due to the lack of its own fissionable isotopes and as such, it cannot be employed in the production of nuclear weapons. Recent trends of nuclear disarmament and accumulation of plutonium from uranium fuel cycle can propel the deployment of thorium. The implementation capacity of thorium nuclear power is estimated to be about 392 GWe at 2050. The utilization of thorium will both help to provide clean energy and to supply rare-earth materials for clean automobiles. In order for us to effect the commercial deployment of thorium resources, establishment of an international framework to supply resources from developing countries as well as to supply technology from developed countries is indeed imperative. Herein, the author propose "The Bank (Thorium energy Bank)" as such a framework.

Keyword: thorium; electricity; transportation; rare-earth; climate change

1 Introduction

The technological revolution of the past few centuries has been fuelled mainly by the combustion of fossil fuels, which has culminated in the vast emission of greenhouse gases (GHGs) such as anthropogenic CO_2 into our atmosphere exacerbating global warming. For the sake of future generations, we need to dedicate our efforts to constructing a sustainable low-carbon society. In addition, with a projected continuous growth of Asian economies, prodigious energy consumption is expected. Thus, we have to seek not only a low-carbon energy supply technology, but also an international framework to comprehensively reduce CO_2 emission.

In this paper, the author will discuss the feasibility of thorium nuclear power as a low-carbon energy source, and describe how it can contribute to constructing a symbiotic energy demand and supply system. Additionally, an international framework to implement thorium nuclear power will also be discussed.

2 What has to be done?

Knowledge regarding the CO_2 emissions from various sectors is indispensable towards implementing economic and technical approaches to combating global warming. About 46 % of CO_2 emanates from energy sectors such as electricity and heat production [1]. The governing factor of CO_2 emissions from electricity production is coal fire plant. Coal is a wide-spread energy resource, owing to its relatively cheap cost and the abundance of its associated reserves. CO_2 emissions from the combustion of coal can be curtailed by adopting CCS (Carbon Capture and Storage). Most of the technical elements of this system have been faced out, and some feasibility studies are being conducted in Norway,

Received date: December 29, 2010
(Revised date: May 6, 2011)

Canada and Australia. However, a succinct and careful design of a complete CCS system will be imperative, in order to obviate CO_2 leakage during its transportation to the final disposal area [2]. Solar power is also available for electricity supply, but its limitation resides in its availability only during daytime and its output fluctuations.

Nuclear power is one of the pragmatic energy sources of low-carbon. Indeed, nuclear power has been recognized as an effective countermeasure to mitigating global warming, but it was not deemed an option for the Clean Development Mechanism (CDM) due to its unresolved concerns. The perceived adverse safety, environmental, and health effects; potential security risks stemming from proliferation; and unresolved challenges in long-term management of nuclear wastes, are among the unresolved problems undermining its commercial deployment. As Solana, the incumbent high representative for the common foreign and security policy of EU said, the expansion of the present nuclear power to the developing countries in Asia will pose nuclear proliferation concerns. The Bhopal and Chernobyl disasters are just two examples among many which are still vivid memories relating to the possible consequences of the use of nuclear energy. Furthermore, the ongoing Fukushima nuclear disaster has revealed the detrimental consequences of nuclear power utilization. Recent trends in the USA have revealed concerns against disposal of radioactive wastes, which contain plutonium (Pu) and trans-uranium materials (TRU) having a very long half-life.

About 23 % of the global CO_2 emissions emanate from the transportation sector [1], which is one of the sectors showing the highest growth rate. Road transport sector occupies *ca.* 73 % of all the modes of transportation [3]. This trend is forecast to continue albeit global warming is advancing at an unsustainable rate currently, since transportation is an essential necessity. With such considerations, reduction of CO_2 emissions emanating from the transportation sector is indeed indispensable if we are to reduce global warming. Although there are several candidates for low−carbon transportation, electric vehicles (EVs) will rapidly increase because the infrastructure of its energy supply has already been established. The key technological components for electric vehicles as well as hybrid-vehicles are batteries and permanent magnet electric motors. Generally speaking, EVs were commercially deployed earlier than gasoline engine cars. However, the technology of EVs could not be incorporated on a large scale basis due to its short driving range. Recent advancements in the shelf-life of batteries and high power electric motors will certainly aid in the replacement of gasoline engine cars with EVs.

A sectoral approach has been suggested as an effective way of reducing GHGs for a post-Kyoto framework. It is however crucial to analyze the advantages and disadvantages of such an approach over the existing Kyoto framework, in order to undertake this approach successfully. One of the advantages lies in its ease in determining the CO_2 reduction targets in each respective country. A sectoral approach also has a number of weaknesses, the prime one being that a sector's reduction has a possibility of becoming another sector's imposition. The most apparent possibility is the electrification of the transportation sector, which currently mainly uses oil as its fuel. It is easy for the transportation sector to significantly reduce CO_2 emissions through electrification. On the other hand, the power sector will be compelled to consider additional reform efforts to reduce CO_2 emissions, which is not their initial responsibility.

Such issues underscore the necessity of discussing comprehensive approaches, which can tackle such phenomena as emission transitions from one sector to another, in order to conduct the sectoral approach effectively.

3 Who have to act?

The other important aspect to designing a suitable approach to reduce global CO_2 emissions is a nation-based CO_2 emission data. China is currently the world's biggest emitter of anthropogenic CO_2 [1], and its emissions are estimated to further increase in the near future due to its massive economic growth and large population. The second biggest emitter of CO_2 is USA. As these two countries occupy about 41% of the global CO_2 emissions, a need therefore exists to consider CO_2 reduction countermeasures for these two great nations.

The current trend of CO_2 accumulation in the atmosphere is mainly as a result of the previous CO_2 emissions from developed countries such as USA, Japan and various European countries. Notable is that there are only a few developing countries featuring in the top 15 list of the highest CO_2 emitting countries. However, we have to be vigilant of the future forecast that developing countries are now growing and will emit more CO_2 than developed countries. Indeed, India is the world's fourth largest CO_2 emitting country and is also the second largest country in population.

With these caveats in mind, it is therefore necessary to consider plausible CO_2 emission reduction methods, which can be adopted as countermeasures against global warming by these developing countries. One of the concerns on energy security is whether energy resources are supplied stably or not. From this point of view, energy resource, which can be obtained within its own land area, is most applicable. Even though there are several limitations, renewable energy sources such as solar power will be a nation's own energy source.

It was suggested that CO_2 emissions have to be reduced in both the power generation sector and transportation sector. It is also necessary that CO_2 reductions effected in one sector do not influence another sector's. These prerequisites have to be considered in the quest to implementing a new approach to China, USA and developing countries such as India.

4 Thorium nuclear power

In spite of the aforementioned concerns, nuclear power can play a pivotal role of availing sustainable energy with very low CO_2 emissions. One of the advantages of applying is that it will satisfy a simultaneous reduction of CO_2 both in the power generating sector and transportation sector. That is to say, if newly installed nuclear power plants supply electricity to electric vehicles, they do not affect the operations of the power generating section.

China has already mentioned about nuclear power expansion plans for providing grid electricity. The number of nuclear power plants under operation is 11, the number of nuclear plants under construction is 12, and the number of nuclear plants China plans to construct is 147. It was not obvious how USA considers nuclear power utilization after the political change from former president Bush to president Obama. However, the incumbent president Obama has reiterated that nuclear power will also be used as a new source of energy. Even more informative is that, there are many countries planning to implement nuclear power in developing countries such as India even after the Fukushima Daiichi nuclear disaster.

Regardless of these pursuits to effect its utilization, concerns pertaining to the use of nuclear power still persist. As such, it will then be necessary to overcome the looming concerns if nuclear power is to be expanded into Asian countries. Nuclear proliferation and radioactive waste, which are deemed the major concerns, occur essentially in as much as only uranium is used as the nuclear fuel. Plutonium is produced from the fertile isotope of uranium (mass number is 238) during the nuclear fission reaction in a reactor. If spent nuclear fuel is reprocessed, plutonium can then be separated. Uranium-235, which is the fissionable isotope of uranium, transforms into fission products and becomes radioactive waste. Uranium-238 produces trans-uranium (TRU) materials such as americium and curium, which are radioactive wastes with a long half-life.

There is a possibility to overcome concerns relating to the use of uranium as a nuclear fuel, through the application of thorium as a nuclear fuel. In this section, a brief outline of thorium nuclear power will be described, and its recent global trend will be discussed.

Thorium is naturally occurring fertile material. Thorium transmutes to fissionable uranium-233 by absorbing neutron as shown below.

$$^{232}Th + n \rightarrow {}^{233}Th \xrightarrow[\text{22m}]{\beta} {}^{233}Pa \xrightarrow[\text{27d}]{\beta} {}^{233}U \quad (1)$$

Thorium is a lighter element than uranium and produces small amounts of plutonium and TRU, owing to the fact that more than 90% of uranium-233 undergoes fission without growing heavier nucleus by neutron absorption. Thorium-based nuclear fuel in a molten-salt reactor produces about 0.5 kg of plutonium, while uranium fuel produces 230 kg of plutonium in a light water reactor of 1 GWe capacity during a one year operation [4]. Significant quantity (SQ) of plutonium is 8 kg for the minimum nuclear explosion. Thus, the production of plutonium in thorium-based nuclear reactor is subtle. In addition to this, spent thorium fuel reaction accompanies a strong gamma ray, which obstructs the manufacture of nuclear weapons by using uranium-233 obtained from thorium-based fuel reactors.

Even more enlightening is, Tatsujiro Suzuki, a member of Japan Atomic Energy Committee, proposed a new approach toward nuclear non-proliferation and nuclear disarmament in 2009. He suggested using thorium-MOX (mixed oxide) fuel in the light water reactors used commercially at present [5].

Major factors of TRU governing the long-term influence are americium and curium radioactive materials. The production amount of these elements is 0.3 g from thorium [4]. It is much smaller than the production from uranium fuel (25 kg). It takes about one million years for the spent uranium fuel that is not reprocessed to be of the same radioactive toxicity as natural uranium. Even with reprocessing, it will require about 100 thousand years. However, about a few hundred years is estimated for the thorium-based nuclear fuel because the amount of americium and curium is subtle.

The relative abundance of thorium is about 4 times to that of uranium, and its resources are widely available in developing countries such as India, China, and Brazil (Table 1). OECD countries such as Australia, Canada and Norway have also large reserves of thorium. USGS announced last year that the USA reserves 915 thousand tons of thorium [6].

We see several ramifications on thorium utilization from a global warming perspective, and not from a nuclear industry viewpoint. Fritz Vahrenholt, CEO of Repower, mentioned in 2001 that although conventional light water reactors (LWR) will not be introduced into Germany or EU, thorium reactors will be a possible option [7]. Utilization of thorium was recommended as one of the technical approaches to curtailing CO_2 emissions in the specialist meeting on climate change in 2007[8]. Additionally, former Australian Governor-General Major General Michael Jeffrey in 2008 said that "while solar has the best prospect of a clean and sustainable energy source, thorium should not be discounted, as it is cleaner and cannot be used to make weapons grade materials"[9].

Table 1 Thorium resource

Country	Reserve [t]	Ratio
Turkey	380,000	14%
India	290,000	10%
Norway	170,000	6%
USA	915,000	33%
Brazil	16,000	1%
Denmark	54,000	2%
Australia	300,000	11%
Egypt	15,000	1%
South Africa	35,000	1%
Canada	100,000	4%
Greenland	54,000	2%
Liberia	1,000	0%
China	388,000	14%
Other	95,000	3%
World total	2,813,000	100%

9 papers discussing about thorium fuel in LWRs, heavy water reactors (HWRs) or molten-salt reactors (MSRs) were presented in the ANFM IV, which is an international symposium on nuclear power. It was motivating that the general chairman of this symposium wrote as follows, 'Thorium fuel cycles may be unusual to many of us in the US, but they are important topics internationally, and are subjects that we must carefully study in order to ensure the future success of our industry.'

In 2007, Tsinghua University organized in tandem with International Atomic Energy Agency (IAEA), an international workshop on thorium utilization in Beijing. Notable is that although China does not have sufficient amounts of uranium resources, she is endowed with huge thorium reserves. Greneche of AREVA accentuated the importance of using semi-breeding reactor with thorium fuel. Besides the fact that CANDU reactor is better than LWR, its conversion ratio (CR) is still smaller than unity. He also mentioned about the aesthetic features of MSR. A second workshop, TU2009, was held in Baotou. Baotou is a city of rare-earth industry, which is indispensable as a material source for EVs. Generally speaking, thorium has already been accumulated as a by-product of rare-earth mining.

The Ministry of Petroleum and Energy of Norway published a report on thorium utilization in 2008 [10]. Several private companies such as “Statkraft” and “Thor Energi AS” are conducting R&D activities on the utilization of thorium as a nuclear fuel. Worthy of mention is, the former secretary general of IAEA, Hans Blix, became a board member of Norwegian thorium fuel company, Thor Energi AS.

In the USA, a section under the title, “Study on thorium-liquid fueled reactors for naval forces” was included in the legislation of the “National Defense Authorization Act for the Fiscal Year 2010”. Finally, the description of thorium-liquid fueled reactors was removed, but $ 61.5 million has been allocated to Oak Ridge National Laboratory (ORNL), which undertakes research and development activities on thorium-liquid fuel reactors.

There were a number of movements among private companies of nuclear industries [11]. AREVA, the French nuclear company, signed a collaborative agreement with US Thorium Power Co. Ltd (currently, Lightbridge Co. Ltd) on the utilization of thorium nuclear fuel. Moreover, AECL, a Canadian nuclear company, signed with China for testing thorium fuel in Chinese CANDU reactors.

A number of popular magazines are highlighting various issues regarding the utilization of thorium. For instance, Newsweek [12] presented an article entitled “The Lost Chance — to return to the road not taken 50 years ago — thorium fuel cycle in 2001.”The Australian scientific magazine, COSMOS, reported in 2007 about the utilization of thorium as a “green nuclear power”[13]. In 2008, Sam Knight also reported about recent situations on UK’s “Financial Times” [14]. In addition, “U.S. News & World Report” published an article regarding thorium utilization in a special issue of green economy in 2009 [15].

An international meeting of thorium energy alliance was held on 29th and 30th March in 2010 at Googleplex - the head-office of Google. Myriad issues concerning the utilization of thorium were discussed, including a high temperature gas cooled reactor and molten-salt reactor called LFTR (Liquid Fluid Thorium Reactor). On October of 2010, a following conference was held in London. Thorium utilization via an Accelerator driven sub-critical reactor (ADSR) was also a remarkable topic of this conference.

One of the most attractive types of reactors for the utilization of thorium is a molten-salt reactor (MSR) [16]. A successful R&D program on the utilization of thorium through MSRs was carried out in the USA since the 1950's to 70’s. Molten-salt reactor experiment (MSRE) was successfully operated during 1965 ～ 1969. Based on this success, molten-salt breeder reactor (MSBR) was duly developed as a target for commercial power reactor [17]. Furukawa *et al.* have notably proposed an MSR design they named FUJI [18]. In fact, MSR was among the 6 generation IV reactors chosen by the 4th GIF.

The inner pressure of the reactor vessel of MSR is only *ca.* 0.5 MPa. Therefore, there is no necessity of fabricating the pressure vessel and this is expected to eliminate the bottleneck residing in the supply chain. The economy of molten-salt breeder reactor (MSBR) has also been analyzed [19]. Comparison between MSBR and LWR using uranium indicate that (1) capital cost will nearly be the same; (2) fuel cycle cost will be greatly reduced since the manufacture of fuel rods is not a requisite and (3) maintenance cost will be reduced because there is no necessity of fuel exchange. Seminal works have revealed the cost evaluation of MSRs and pressurized water reactors (PWRs) in view of capital cost, operations and maintenance, fuel, waste disposal and decommissioning [20]. The results are summarized in table 2. The fuel cost of an MSR was recalculated based on the utilization of uranium-233. The total cumulative cost of an MSR will be about 30 % lower than that of a PWR’s. The current cost of nuclear power is about half that of fire power [21].

Table 2 Cost evaluation of MSR and PWR (cent/kWh)

	MSR	PWR
Capital cost	2.01	2.07
Operations & maintenance cost	0.58	1.13
Fuel cycle cost	0.12	0.74
Waste disposal cost	0.10	0.10
Decommissioning cost	0.04	0.07
Total	2.85	4.11

-Short term … LWR, HWR etc. (by USA, Canada, France, India etc.)
-Middle term … MSR (by Czech Rep., US Navy?, China?, India?)
-Long term … Breeder based on ADS (by USA etc.)

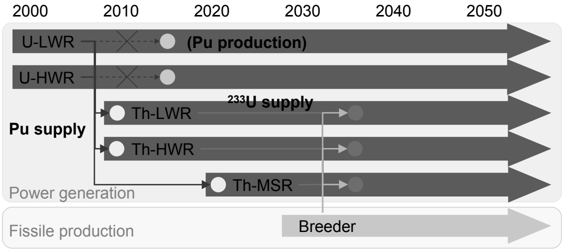

Fig.1 Implementation path of thorium nuclear power.

As aforementioned, thorium is often obtained as a by-product of rare-earth metals, but it is still not utilized as a nuclear fuel currently due to the lack of its own fissionable isotopes and as such, it cannot be employed in the production of nuclear weapons. Recent trends of nuclear disarmament and accumulation of plutonium from uranium fuel cycle can indeed propel the deployment of thorium.

In spite of its advantages, thorium was not utilized as a nuclear fuel in commercial nuclear reactors, save for a few cases. One of the reasons behind was that thorium does not contain fissile isotope. However, this problem can be circumvented through the utilization of plutonium in spent nuclear fuel of LWR [22, 23]. Another reason is that plutonium is the artificially produced material *per se*, thus there was no adequate amount of plutonium in the 1970's to power thorium reactors. Currently, there is about 200 thousand tons of spent nuclear fuel, containing 2,000 tons of plutonium. It is noteworthy that, annually, there is at least 12,000 tons of spent nuclear fuel depending on the total capacity of LWR in the world [24]. Czech, Japan and France are conducting intensive research on thorium utilization of thorium via the usage of spent plutonium fuel from LWRs as well as MSRs. A direct fluorination facility, named FERDA, has been developed in order to obtain plutonium from spent nuclear fuel [25].

An outline summary of an implementation path for thorium utilization, incorporating recent technologies such as LWR and the novel MSR, is shown in Fig. 1.

The most important point of thorium utilization is a fissile supply. Fissile material will only be plutonium resulting from the uranium fuel cycle in the initial stage of thorium utilization. While it is true that plutonium can also be used in the uranium fuel cycle, uranium-235 can be fed to the uranium fuel cycle directly from natural resources and this process has been perpetuated for more than 50 years. In consideration of constructing additional nuclear power supply for sustainable energy sources, there should be a continued usage of this uranium fuel cycle and thus, the plutonium obtained from the uranium fuel cycle can be incorporated in the thorium fuel cycle since thorium does not contain fissile isotopes.

This will enable the uranium fuel cycle to be at a commercialized situation in power generating industry and additionally, power supply from thorium can be implemented although not an alternative power source. Uranium-233 is produced during the operation of thorium fuel in both LWRs and HWRs, and can be utilized in the thorium fuel cycle *per se*. Although it is not yet commercialized, there are lots of processes to be realized in using MSRs. MSRs can be run on thorium fuel in lieu of uranium fuel, because it will not significantly affect the present energy supply system based on the uranium fuel. It is projected that it will take more than 10 years for commercial realization of MSRs as a nuclear power reactor. The uranium-233 that is produced from the utilization of thorium fuel in LWRs and HWRs, will be stored and then utilized as a fissile material for new fuel in the future. In addition, uranium-233 will be produced by using an accelerator, owing to the fact that plutonium supply from uranium fuel cycle is still kept in small amounts.

The implementation capacity of a thorium MSR in a global scale was calculated based on the plutonium supply from the uranium fuel cycle. Here, two different designs of MSRs were considered: one of them being, FUJI-Pu2 [26] and the other, FUJI-U3 [27]. The former uses plutonium as the initial fissile material and the latter uses uranium-233 produced by FUJI-Pu2. The total requirement of plutonium and uranium-233 during its lifetime (30 years) is 6.94 tons and 1.476 tons, respectively. The electricity capacity of these reactors is 200 MWe. Calculations were determined using the following protocols. First, the capacity of uranium fuel cycle at a certain year was determined. The production of the spent nuclear fuel was thereafter obtained. It was assumed that MSRs will commence operation as from around 2020. The MSRs capacities were projected to grow gradually and based on such assumptions, the corresponding amount of plutonium was calculated. Note that this amount is for the spent nuclear fuel, and the capacity of processing spent nuclear fuel to molten-salt fuel is assumed to be sufficiently high. Calculation results are shown in Fig. 2.

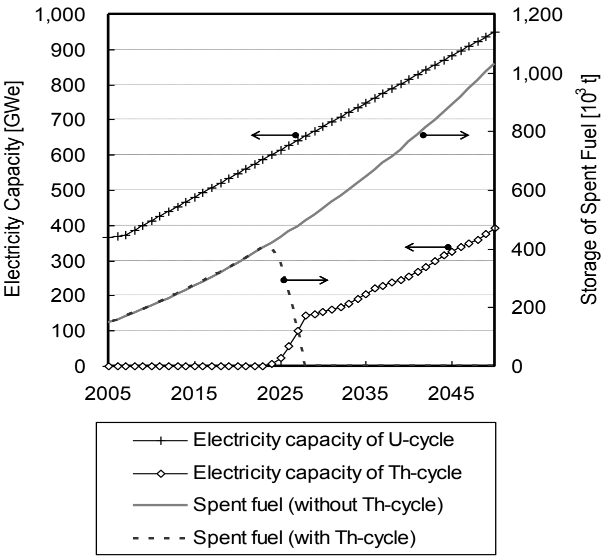

Fig.2 Implementation capacity of thorium MSR.

The black cross line indicates the growth of LWRs. These estimations are based on the predictions by OECD/IEA [28]. The gray line corresponds to the stored spent nuclear fuel without MSR, while the black chain line represents the stored spent nuclear fuel with MSR. White rectangles represent MSRs. MSRs are expected to commence operation from 2024, and the capacity of LWRs and MSRs is projected to be 948 GWe and 392 GWe, respectively at around 2050.

Thorium MSR also produces its own spent nuclear fuel. However the amount is considerably smaller than the amount from an uranium LWR. This is because the spent fuel of a thorium MSR comes out of the reactor after completing 30 years of its lifetime. On the other hand, the spent fuel of LWR occurs once every year. It is herein estimated that thorium MSRs will be commercialized in the 2020's, and as such, the spent fuel of thorium MSRs will appear around 2050's. A quantitative evaluation has been demonstrated in our previous work [22].

5 Sustainable development for Asian countries

5.1 Production of thorium as a by-product of rare-earth for transportation sector

From a sustainability point of view, another crucially important sector is the transportation sector. Myriad automobile companies have pledged to supply EV or hybrid-vehicle (HV) recently as is summarized in Table 3. In 2009, Reborn GM in 2009 announced the production of the “Chevrolet Volt” concept EV, which saw the company receive the coveted “2011 Green Car of the Year” award. Many EV companies have emerged in China, making China the world’s largest car producer and seller. BYD, which was only a battery company, is one of the most famous EV companies in China.

Table 3 Development of Low-Carbon Vehicle

	Company	Brand
Japan	Toyota	Prius (HV)
	Nissan	Leaf (EV)
	Honda	Insight (HV), CR-Z (HV)
	Mitsubishi	i-MiEV (EV)
EU	VW	New compact coupe (HV)
	Audi	e-tron (EV)
	BMW	MINI E (EV)
	Daimler	Smart EV (EV)
	Renault	Z. E. (EV)
	PSA	OEM, Mitsubishi (EV)
USA	GM	Chevrolet Volt (EV)
	Ford	Focus EV (EV)
	Tesla motors	Roadster (EV)
Korea	Hyundai	i10 electric (EV)
China	BYD	e6 (EV)
India	Tata	Indica Vista EV (EV)

Rare-earth materials such as neodymium and dysprosium are utilized in fabricating strong electric motors. The world’s annual production of rare-earth materials was about 120 thousand tons as at 2010 [29], and the production amount is expected to increase by about 3 to 5% every year. Currently, China accounts for about 97% of global rare-earth production, the remaining reserves of which have been verified to exist in other Asian countries. However, thorium is obtained as radioactive waste during the refining process of rare-earth [30] materials, posing a serious impediment for their utilization in various applications.

As aforementioned, thorium is not utilized as a nuclear fuel, and is thus left as radioactive waste, and this will raise environmental and social concerns at the resource countries. Annual production of residual thorium is estimated to be at least 10 thousand tons, although a detailed investigation is required to determine the accurate values. In summary, limitations associated with handling rare-earth materials makes it difficult for Japanese trade companies to utilize such materials.

5.2 Thorium consumption

Consumption of thorium has also been simulated by using the capacity of thorium nuclear fuel. The simulation result is shown in Fig. 3.

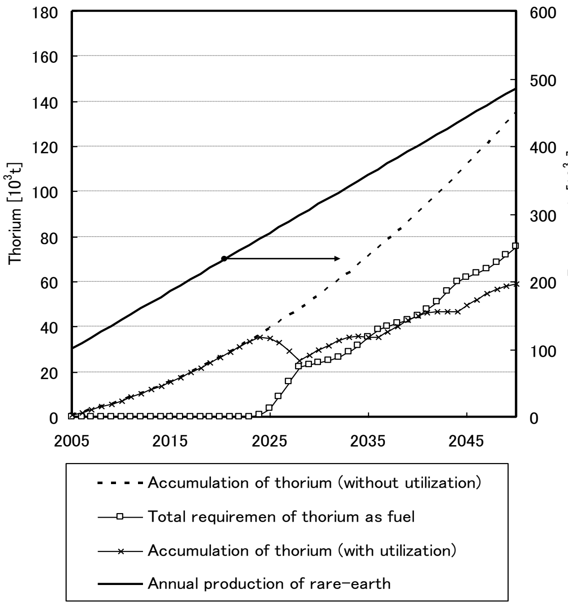

Fig.3 Consumption of thorium.

Here, it is assumed that *ca.* 1% of rare-earth production corresponds to the amount of thorium. It is also assumed that the initial value of thorium storage at 2005 is zero. Typical models of thorium reactors FUJI-Pu2 and FUJI-U3 require 31.3 tons and 56.4 tons of thorium as initial value, respectively. Stockpile of thorium will be about 40 thousand tons at around 2024, when the commercial utilization of thorium reactors commences. Though thorium will be produced in parallel with the production of rare-earth material, thorium will also be consumed and the stockpile will be about 60 thousand tons at around 2050. If there is no utilization of thorium, its stock will be more than 130 thousand tons.

5.3 CO_2 reduction from transportation sector

CO_2 emissions from transportation sector have been simulated based on the prediction of the capacity of thorium MSR. The results are shown in Fig. 4.

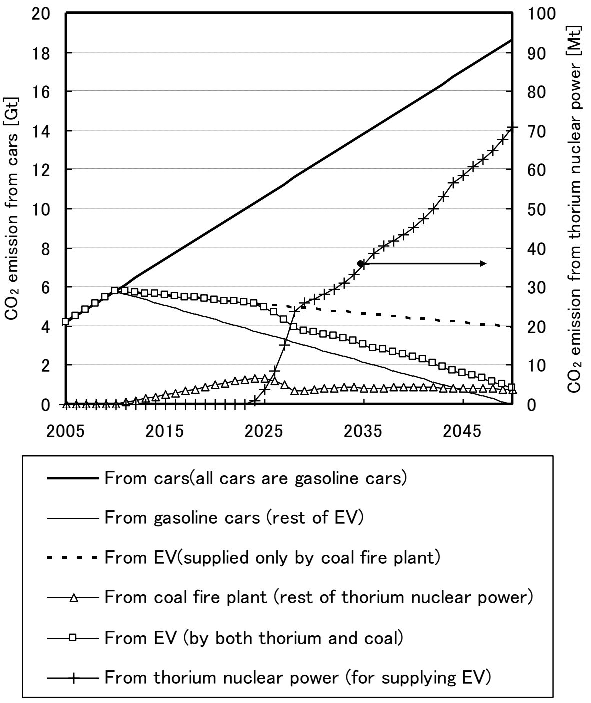

Fig.4 CO_2 reduction by thorium utilization.

It was assumed here that number of vehicles increases at a 3.5% of growth rate, which is akin to the recent trend [31]. The total number of vehicles in the world at around 2005 was about 900 million, emitting 4.5 G tons of CO_2 into the atmosphere. It is projected that as at 2050, there will be about 4 billion vehicles and as such, 18.6 G tons of CO_2 will be dissipated into the atmosphere. If 100 million EVs are supplied every year, starting from 2010, all gasoline vehicles can be replaced with EVs by 2050. Even though this estimation is somewhat large, it was tentatively assumed in order to evaluate higher cases of CO_2 reduction. It is also assumed that 1 kWh of energy is sufficient to drive an EV for 10 km, and the average mileage coverage per year is approximately 10,000 km. 392 GWe of thorium nuclear power plant can supply electricity to 2.75 billion EVs, provided that the EVs are supplied with electricity harnessed from thorium nuclear power with a load factor of 80%. This value corresponds to 60 million tons of CO_2 emissions emanating from thorium nuclear power. This was calculated taking into account that 1 kWh of nuclear power emits 0.022 kg of CO_2, and with a load factor of 80%. If the rest of the 1.25 billion cars are also EVs and supplied with electricity generated from coal fire plants, global CO_2 emissions is 1.23 G tons. The coal fire plant was estimated to emit 0.975 kg of CO_2 per 1 kWh and thus, the total CO_2 emission from both thorium nuclear power and coal fire plant is 1.29 G tons. It is apparent that solving problem pertaining to the sectoral approach via a collaborative utilization of thorium nuclear power and EVs has a great potential of reducing global CO_2 emissions.

5.4 Concept of "The Bank"

Implementation capacity of thorium nuclear power is influenced by the amount of fissile material supply. Thorium is deemed a radioactive waste and also a residual of rare-earth mining. As indicated in Fig.3, thorium will not completely be consumed even though it is utilized as a nuclear fuel. Therefore, there is a likelihood of thorium, which is not appropriately handled, causing environmental hazards and risks. For us to bolster the advancement of EVs in order to achieve substantial reductions in global CO_2 emissions from the transportation sector, rare-earth mining as well as a careful handling of associated radioactive material is indeed indispensable. Estimation of the implementation capacity of thorium nuclear power is based on the fissile material supply from the uranium fuel cycle owing to the fact that thorium does not contain its own fissionable isotope. Another point worth mentioning is that it will require more than 10 years for the first commercial implementation of thorium nuclear power. There are several countries, which consider thorium-based nuclear power as future's energy source like India, but most of the countries have no plan to store thorium. A need therefore exists to find ways of storing thorium.

Such considerations in mind motivated us to propose herein the concept of "The Bank", named from "thorium energy bank". An outline of "The Bank" is illustrated in Fig. 5.

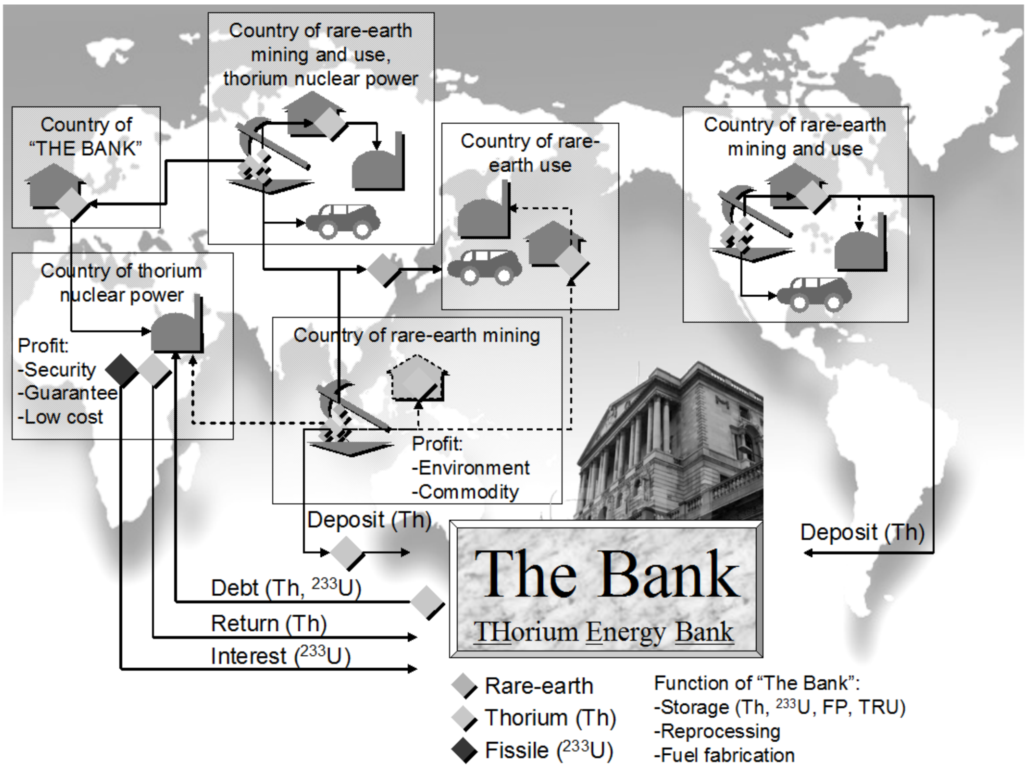

Fig.5 Concept of "The Bank".

The prime purpose of "The Bank" is to store thorium obtained as residual of rare-earth mining. This is crucially important in order to mitigate the hazardous environmental effects of thorium radiation. Another function is to lend thorium to countries that are not endowed with their own thorium reserves. Former US president Jimmy Carter notably proposed a concept of "a nuclear fuel bank", charged with the responsibility of providing fissile material (in this case, enriched uranium). It is worthwhile mentioning that this concept was proposed in a bid to control the expansion of uranium enrichment technologies for fear of nuclear proliferation. A similar proposal was also broached by the former director of IAEA, Dr. ElBaradei. In his Prague speech, US President Obama also pointed out the pivotal role of the nuclear fuel bank concept in bringing greater global peace and security. In view of this, "The Bank" will accept both thorium and uranium-233 as a fertile and fissile material, respectively.

However, "The Bank" will not have any uranium- 233 at the nascent stage of its operation. Thus, other fissile materials such as plutonium must be obtained from the uranium fuel cycle. Once thorium fuel is is utilized by a certain country, the spent thorium fuel will be returned to "The Bank". As indicated in Fig.5 above, uranium-233 will be the interest that accrues thorium fuel debt. Currently, there is much more demand for rare-earth materials than is for thorium resources, and therefore we expect the trend of demand toward rare-earth and thorium to be somewhat different.

"The Bank" will be an international organization, whose head office will be located in countries which have no risk of nuclear proliferation such as Norway, Sweden, Australia and Japan. It will be worthwhile if the country in which the head office is located in has technological knowhow regarding the safe handling of radioactive materials. The head office will have several functions, one of which being to store separated thorium during the refining process of rare-earth mining. The stored thorium can be lent to countries, and these countries have to return both thorium and fissionable uranium-233 in the spent thorium fuel to "The Bank". Uranium-233 is produced by absorption of neutron of thorium. As aforementioned, uranium-233 is the interest pledged against the debt of thorium from "The Bank". So long as the capacity of thorium nuclear power in the world is limited by the supply of plutonium from the uranium fuel cycle, the amount of thorium produced from rare-earth mining should be greater than the consumption amount of thorium as nuclear fuel. It is thus to be noted that the price of thorium will be kept at a low level.

Another function of "The Bank" is to reprocess spent thorium fuel. If light water reactor or heavy water reactor is used as a nuclear power reactor, solid fuel rods including thorium and fissile materials (uranium-233 or plutonium) will be returned. If molten-salt reactor is used, frozen fuel salt will be returned. For the former case, a direct fluorination method called FERDA will be employed to obtain plutonium and uranium-233 from solid spent fuel. As for the latter case, a dry-process method using molten-salt will be employed in reprocessing of the fuel.

The last function of "The Bank" is to fabricate thorium fuel. Depending on international discussions, there is a likelihood of countries planning to implement thorium nuclear power not being allowed to have fuel fabricating facilities. United Arab Emirates (UAE) can be considered as a case example. UAE has signed international agreements with USA regarding the utilization of nuclear power. UAE implements nuclear power plant but they do not have enrichment and reprocessing facilities. Nuclear fuel will be fed by USA and spent nuclear fuel will be sent to France or other countries. "The Bank" will have several branch offices. The function of the branch office will solely be to store and lend thorium.

It is necessarily not a compulsion for all the countries to join this framework of "The Bank". Some countries such as India that are endowed with rich reserves of thorium, and have facilities for re-processing and fabrication of such fuel can progress with their own plans. We recognize India's role in spearheading thorium fuel utilization. The function of "The Bank" will be more conducive to countries having rare-earth resources but lacking plans for thorium utilization. South-East Asian countries such as Vietnam or Myanmar will serve as a case example.

Recently, there are many researches being conducted on breeding of uranium-233 from thorium through the utilization of accelerator or fusion technologies. In spite of these efforts, however, it is forecast to take more than 20 years for commercialization of uranium-233 production from thorium. Therefore, it is necessary to store thorium until its utilization for large scale energy production is implemented unhindered.

5.4 Symbiotic approach to the sustainable society

The direct utilization of thorium as nuclear fuel is apparent, and as described before, thorium will play a pivotal role in establishing a sustainable society. However, from a sustainability point of view, there are myriad relevant fields of application such as uranium fuel cycle, electric vehicle and rare-earth metals mining. A comprehensive approach of utilization of thorium is illustrated in Fig. 6.

Figure 6 demonstrates the material balance of thorium utilization. In order to utilize thorium as a fertile material of nuclear fuel, some fissionable materials such as plutonium is necessary and its adequate amount is also required. Thorium has been known as a nuclear fuel since the 1940's, but it was impossible to use thorium as a commercial nuclear fuel owing to the lack of fissionable material. It is becoming possible to supply plutonium as a fissionable material for the utilization of thorium in the beginning of 21st century. Transportation sector adopts EVs because it does not emit CO_2 during operation. Thorium is produced on a daily basis as a residual of rare-earth metal mining, and this can be fed to the thorium fuel cycle. Indeed, EVs would not be used if climate change was not a significant issue for mankind. Even more relevant is that the amount of rare-earth metal mining has been increasing over these 10 years.

Other comprehensive approaches of thorium utilization, in view of the demand and supply sides of electricity and material, are illustrated in Fig. 7. One of the many approaches to optimizing energy utilization is balancing the demand and supply. The concept of smart grid systems will aid in both the optimization of energy utilization, and implementation of clean energy sources such as solar and wind power. Smart meters attached at each house or office will feedback demand information to the supply side. These smart meters also ensure the wise utilization of electric facilities at the demand side. It is also notable that renewable energy will be used at the demand side. In fact, utilization of solar power through the employment of photovoltaic cells is one of such commercialized energy sources. This can

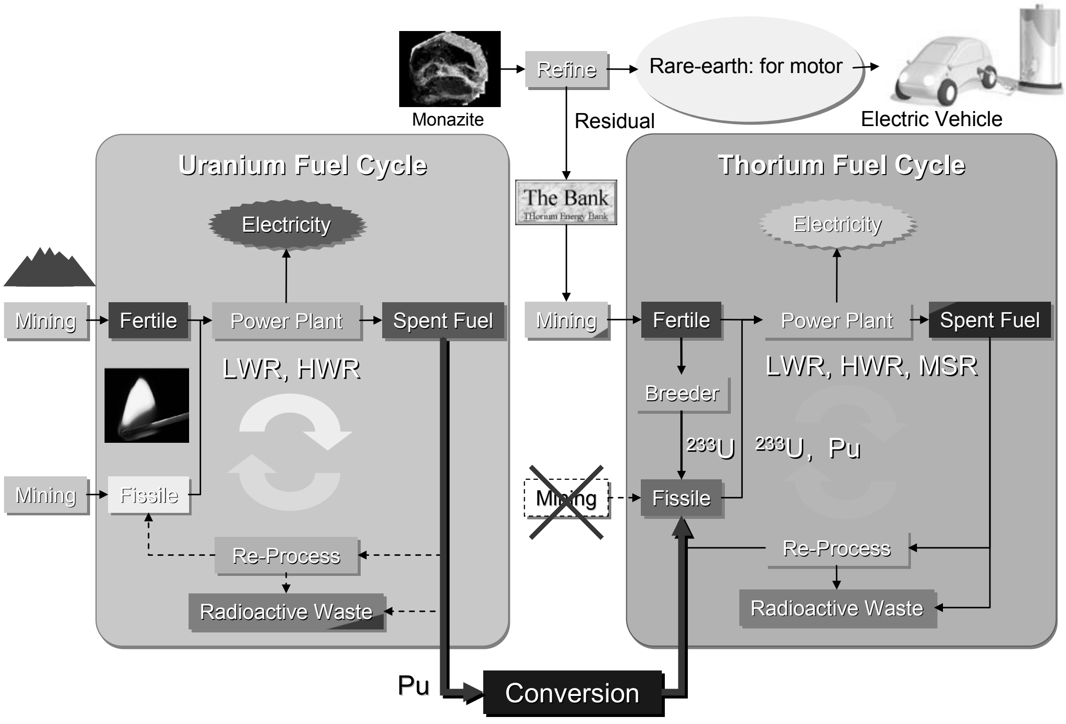

Fig.6 Comprehensive approach of thorium utilization.

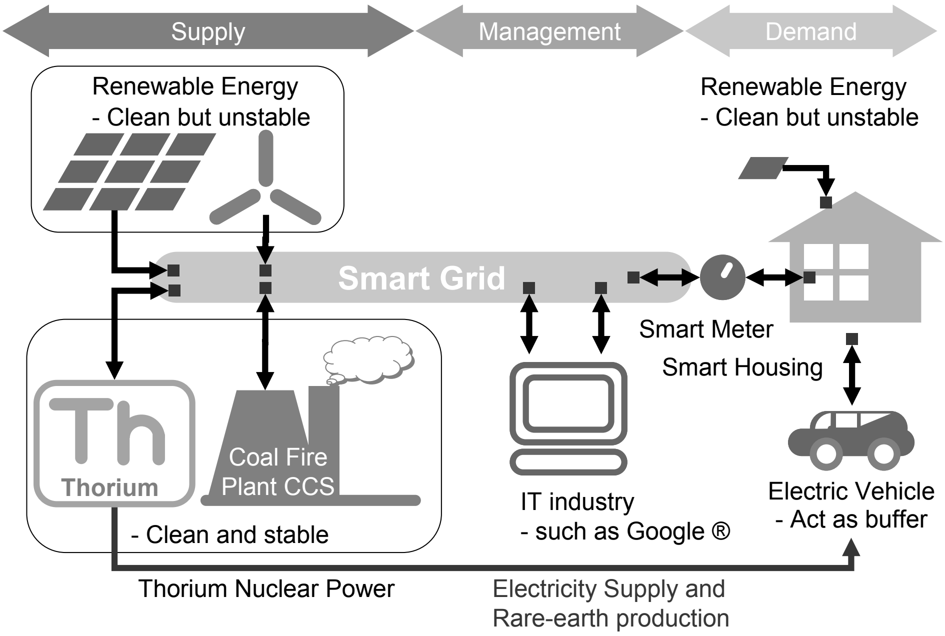

Fig.7 Smart Grid with thorium utilization.

provide clean electricity, but its output is not stable because of sunlight fluctuations. EVs parked outside houses may play essential roles of buffering the output electricity fluctuations resulting from these unstable energy sources.

Renewable energy will be widely used at the supply side, but it is in essence not stable and cannot monitor the change of load. Therefore, other energy sources, which can be operated in load following mode, will be required in order to install renewable energy. Coal fire plant is one of such potential candidates

Coal is abundant and can also be obtained in developing countries, and as such it is still deemed a low cost fuel. Furthermore, CCS (Carbon capture and storage) will be applied in order to reduce CO_2 emissions emanating from coal fire plants. The other load following energy source is thorium nuclear power. There are some limitations in changing the output in commercially-used light water reactor in order to maintain the integrity of fuel rods, but these reactors are operated in load following mode in France. Molten-salt reactor, which uses liquid fuel, has more salient features in operating under load following mode, since it does not utilize fuel rods. In addition, thorium is obtained as residual of rare-earth mining, which is indeed indispensable for EVs.

6 Conclusion

Recent trends in thorium nuclear power are described and its symbiotic approaches are demonstrated from a sustainability point of view. There are many aspects to constructing a sustainable society such as power generation, transportation, waste management, resource control and so on. Thorium has a strong correlation with rare-earth material and EVs, and thus a collaborative implementation of thorium nuclear power and EVs will in principle significantly contribute in CO_2 reduction. Thorium utilization will reduce the environmental hazards and risks residing from illegal disposal of thorium. Despite the projected abundance in thorium and other rare-earth resources in South-East Asia, the potential of thorium as a nuclear fuel resource has not been investigated extensively due to its low possibility in utilization. While there are myriad advantages that underlie thorium utilization, there are still challenges to be met in pursuit of its worldwide commercialization. One of the challenges to face includes a complete technological protection for nuclear proliferation [32]. Frankly speaking, we believe that the utilization of thorium as well as other rare-earth metals will revolutionize the industrial fundamentals.

Acknowledgement

This work was supported by KAKENHI (2171015 2) for Grant-in-Aid for Young Scientists (B).

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