# A Roadmap of Innovative Nuclear Energy System

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**Abstract**. Nuclear is a dense energy without $CO_2$ emission. It can be used for more than 100,000 years using fast breeder reactors with uranium from the sea. However, it raises difficult problems associated with severe accidents, spent fuel waste and nuclear threats, which should be solved with acceptable costs. Some innovative reactors have attracted interest, and many designs have been proposed for small reactors. These reactors are considered much safer than conventional large reactors and have fewer technical obstructions. Breed-and-burn reactors have high potential to solve all inherent problems for peaceful use of nuclear energy. However, they have some technical problems with materials. A roadmap for innovative reactors is presented herein.

## 1. Introduction

The Society of Chemical Engineers, Japan recently published Energy Technology Roadmaps of Japan - Future Energy Systems Based on Feasible Technologies Beyond 2030. I was in charge of writing the part of Nuclear Power Generation [1]. Though this roadmap is a Japanese roadmap, the main part of it discusses the relations between nuclear developed countries and developing countries, and the potentials of innovative nuclear reactors solving the problems we are facing. The present paper is written by modifying the above Roadmap of Japan and tried to make general discussions on the worldwide researches and developments of innovative nuclear reactors appropriate to the International Conference on Advances in Nuclear Science and Engineering.

Global warming is an increasingly urgent problem in the world. Nuclear power is one of the few technologies that can mitigate climate change by reducing $CO_2$ emission [2]. After the slumped period and the 21$^{st}$ century started, the number of nuclear reactors in the world started to increase. However, the Fukushima-Daiichi accident greatly influenced the atomic energy programs for many countries. Now the number of nuclear reactors starts to increase again, but the public acceptance becomes much more difficult than before in many countries.

Nuclear energy not only has a safety problem but also several difficult problems caused by generated radioactive materials and technologies in common with nuclear weapons production. However, it has unique merits such as extremely high energy density, abundant resources, and zero $CO_2$ emissions.

According to a nuclear energy roadmap from international agencies [3], the capacity of nuclear energy will not change from the present through 2050 in OECD countries, but will grow rapidly in developing countries. Developed countries should help developing ones successfully use nuclear energy. Safe, simple and easy reactors are required for developing countries.

Some small reactors (SRs) have these features, although their economy is a difficult challenge to overcome. Breed-and-burn reactors (B&BRs) have high potential to overcome all the above problems, but several technical problems await solution.

The following section describes fundamental characteristics of nuclear energy. A brief history and present status are presented in Section 3, and prediction of nuclear energy by international organizations is addressed in Section 4. Innovative nuclear energy is the topic in Section 5, where we address SRs and B&BRs. A technology roadmap is presented in Section 6, and benefits and future vision are addressed in Section 7.

## 2. Fundamental Characteristics of Nuclear Energy

Humans (not modern humans but Homo erectus) started to use/control the fire on woods about a million years ago. The wood fire is considered as a stored energy, and we can obtain and use whenever we need. It was a turning point in the cultural aspect of human evolution that allowed humans to cook food and obtain warmth and protection. It developed civilizations. The scale of this use and its environmental effects were small. Humans began to use another stored energy, fossil fuels, on a large scale several hundred years ago and this made possible the industrial revolution and modern civilization. Huge amounts of this energy can be used whenever required. Their consumption rate increased rapidly, and resource and environmental problems have become urgent issues.

Nuclear energy, which is also a stored energy, was discovered in the middle of the 20th century. The important feature of the stored energy is its density (specific energy). A list of energy density for several fuel materials is shown in table 1 [4], where one can see a large difference (about a million times) of energy density between nuclear and fossil fuels. Compared with fossil fuels, nuclear energy has several merits in addition to the greater density, such as no $CO_2$ emission and no oxygen requirement.

**Table 1.** Energy density [4]

| Fuel material | Energy type | Specific energy (MJ/kg) | Direct uses |
|---|---|---|---|
| Uranium (in breeder) | Nuclear fission | 80,620,000 | Electric power plants (nuclear reactors) |
| Thorium (in breeder) | Nuclear fission | 79,420,000 | Electric power plants (nuclear reactors) |
| Hydrogen (compressed at 70 MPa) | Chemical | 142 | Rocket engines, experimental automotive engines |
| LPG (including Propane / Butane) | Chemical | 46 | Cooking, home heating, automotive engines |
| Jet fuel | Chemical | 43 | Aircraft |
| Fat (animal/vegetable) | Chemical | 37 | Human/animal nutrition |
| Coal | Chemical | 24 | Electric power plants, home heating |
| Carbohydrates (including sugars) | Chemical | 17 | Human/animal nutrition |
| Protein | Chemical | 17 | Human/animal nutrition |
| Wood | Chemical | 16 | Heating, outdoor cooking |
| TNT | Chemical | 4.6 | Explosives |
| Lithium battery (non-rechargeable) | Electrochemical | 1.8 | Portable electronic devices, flashlights |
| Alkaline battery | Electrochemical | 0.67 | Portable electronic devices, flashlights |
| Lead-acid battery | Electrochemical | 0.17 | Automotive engine ignition |

The means for releasing nuclear energy were discovered during the World War II. One of the main objectives of this war was to secure energy, especially oil. Nuclear energy became another energy resource. Figure 1 shows the resource amount and available period for each energy resource, estimated by the author more than 20 years ago [5]. Resource amounts for this graph were obtained from data available at that time. The values may be considerably different today, but the differences are sufficiently small for the present discussion. The available years were obtained by dividing resource amounts by total annual energy consumption in the future, 0.32 ZJ/year (1 ZJ = $10^{21}$ J). Because several energy types are typically used in a mixed manner, actual available periods are considered to be longer than the values shown.

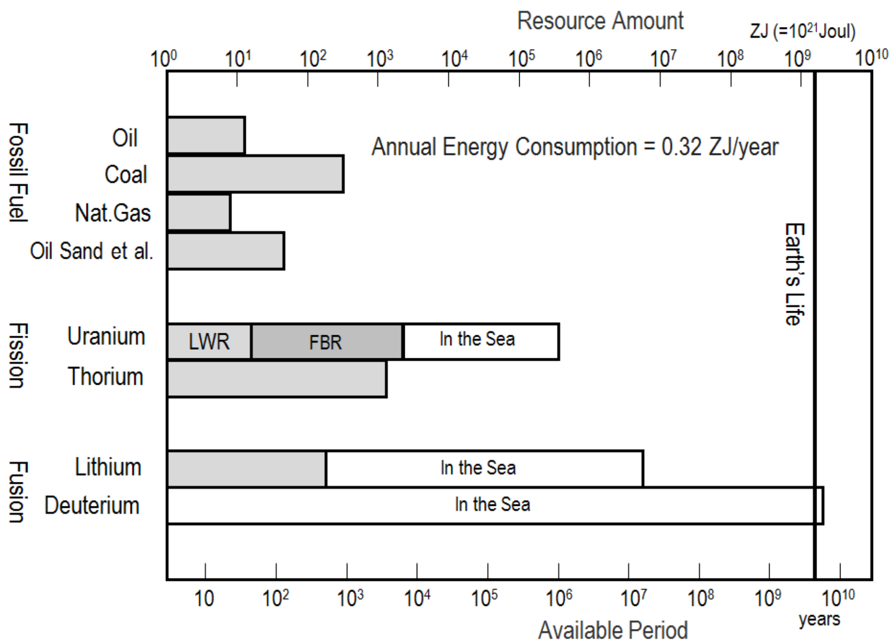


**Figure 1.** Estimated resource amount and available period for individual energy resources [5]

There are dwindling supplies of fossil fuels. Even for the nuclear energy, if only light water reactors (LWRs) with uranium fuel are used, nuclear energy sources can also provide only short-term supply, since LWRs can utilize only less than 1% of natural uranium.

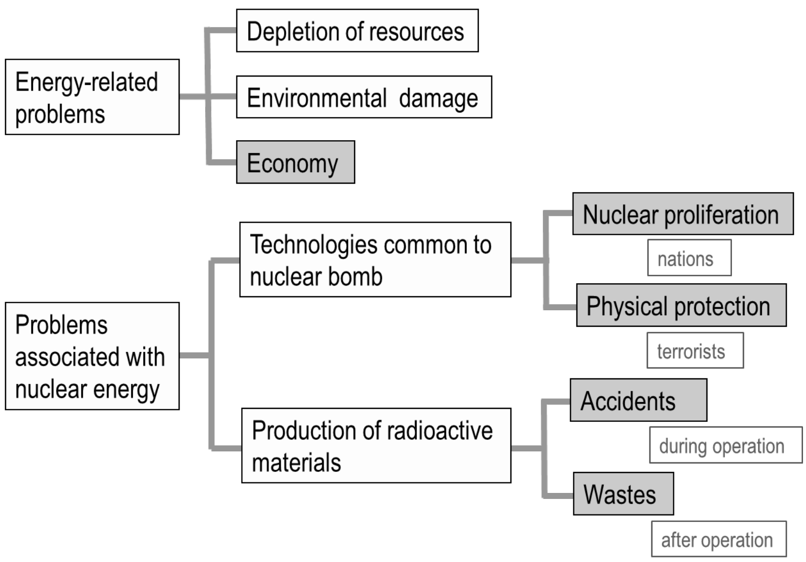


**Figure 2.** Necessary and sufficient requirements for nuclear energy systems [7]

Nuclear reactors produce substantial radioactive materials during operation. This can cause devastating accidents during reactor operation and a problem with radioactive wastes, even after operation cessation. Another inherent problem of nuclear energy is that it uses materials and technologies that are closely related to atomic bomb production. Problems associated with these bombs require implementation of measures for safeguards, terrorist threats, and nuclear proliferation. In this work, we simply call these problems nuclear threats [6]. Cost effectiveness is always an important requirement for energy. Thus, for nuclear energy to be used as a primary energy, all problems associated with a) limited resources, b) safety, c) waste disposal, d) nuclear threats, and e) cost must be solved (figure 2) [7].

For a), the resource problem, fast breeder reactors (FBRs) can use almost all natural uranium. It can extend the fuel available period by almost a hundred times. It also increase the value of natural uranium by almost a hundred times. It means expensive uranium such as uranium in the sea water becomes available as a cost competitive fuel. Then the available period can be extended by almost 10,000 times (figure 1). It is considered enough for humans. For b), the safety problem, after the Three Mile Island (TMI) accident, several SR concepts were proposed [8], which are addressed in detail in Section 5.1. For c), the waste problem [9], at present only underground disposal is promoted in most countries having operational nuclear reactors. However, it is difficult to obtain public acceptance in many countries, and innovative technologies such as transmutation of long-life radioactive wastes are under study. Another creative solution to this problem is proposed in Section 7. The nuclear threats problem, d) [6], is related to peaceful use of nuclear energy, but the relationship is not simple. Even if peaceful use ends, the risk of nuclear threats will persist. If care of nuclear materials and technologies is inadequate, the situation will become worse than the present peaceful use situation. We should develop a peaceful use system that strongly protects against this problem. Regarding e), the cost problem is common to most issues related to daily life, and this is strongly tackled even at present.

## 3. Brief History and Present Status

Nuclear energy was discovered during study on basic physics in the 20th century. In the beginning, release and utilization of this energy by humans were considered impossible. However, fission was discovered in 1939, the possibility of sustainable chain reaction of neutron-induced fission was confirmed, and the criticality of CP1 was achieved in 1942. Since then, many nuclear reactors have been constructed and operated, for military purposes in the beginning and later for peaceful uses [10]. The development of nuclear power began with 6 MWe graphite-moderated water-cooled reactor ONPP which was constructed in 1951 and started to produce electricity to supply to a conventional transmission grid in1954 in the USSR, followed by 60 MWe Shippingport PWR which was constructed in 1954 and began generating electricity in 1957 in the USA.

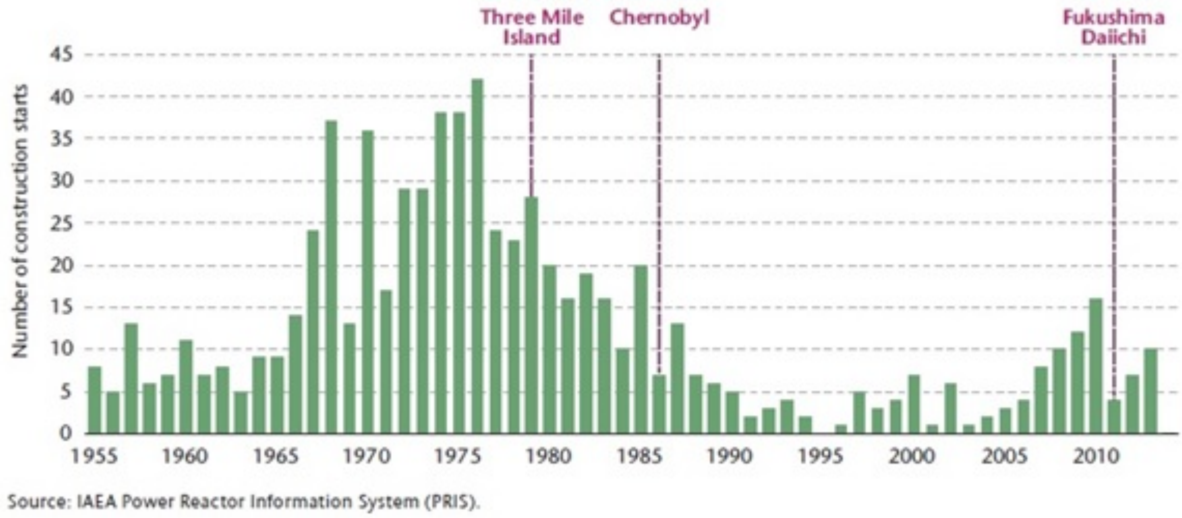


**Figure 3.** Nuclear reactor construction starts, 1955–2014 [3]

The number of construction starts for nuclear reactors every year from 1955 until 2014 is shown in figure 3 [3]. The number generally increased from the beginning through around 1975, when the contribution of the USA was dominant, then decreased to nearly zero around 1995. Since the mid-2000s, the number of reactors constructed has been trending upward, largely because of rapid development in China. Years of the three major accidents (TMI, Chernobyl, and Fukushima) are also shown in figure 3. Despite the serious damage from the Fukushima accident, the recent upward trend appears sufficiently strong for increase in the future.
Most reactors recently constructed are PWRs and their power level are more than 1000 MWe.

## 4. Nuclear Energy Prediction by International Organizations

The Nuclear Energy Agency (NEA) and International Energy Agency (IEA) recently published "Technology Roadmap - Nuclear Energy" [3] in which they show electricity production by technology in the 6 °C and 2 °C scenarios (6DS & 2DS) (figure 4). Although the renewable and nuclear contributions are not substantial in the 6DS, they become so in the 2DS. The large share of renewables in 2DS significantly changes the nuclear operating environment, since the power output of renewables changes drastically even in one day. Nuclear power is traditionally operated to meet baseload demand. It is difficult for both PWR and BWR to execute rapid load-following to meet the changes brought by renewables. New designs are required for this purpose.

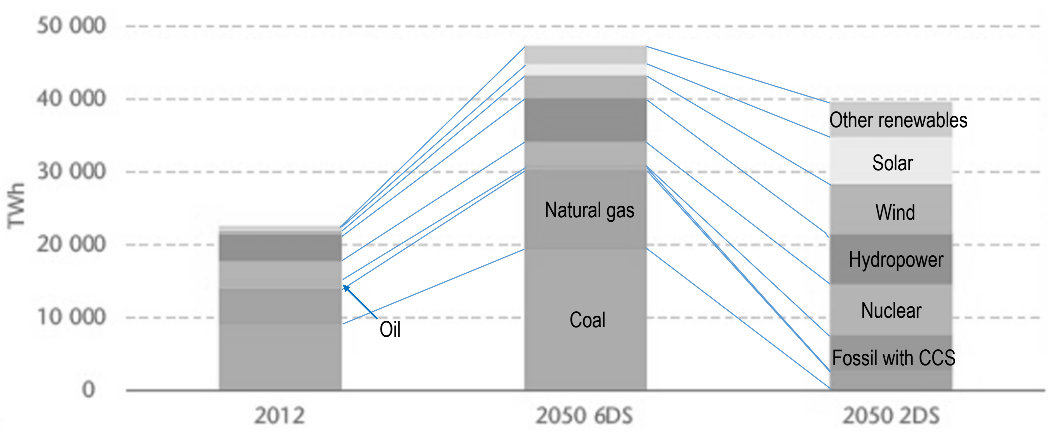


**Figure 4.** Electricity production by technology in 6DS and 2DS [3]

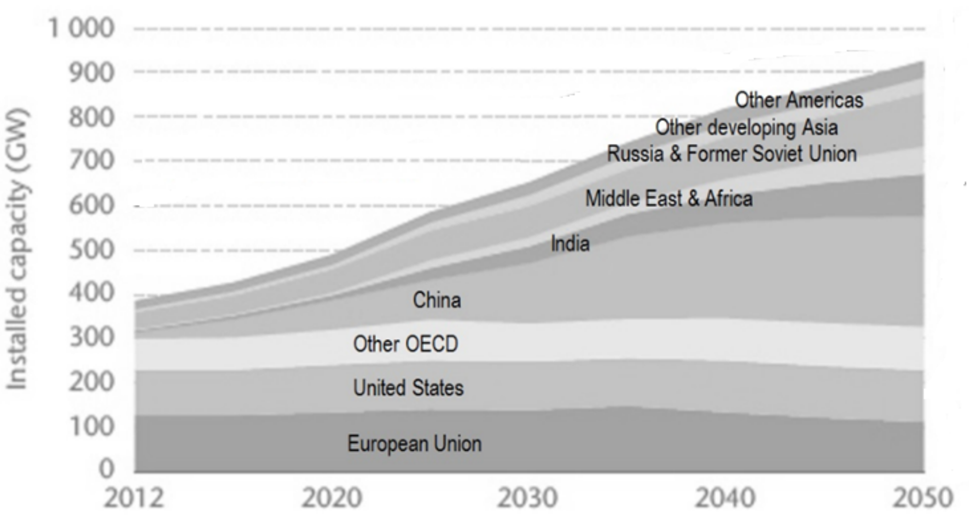


**Figure 5.** Nuclear generation capacity in the 2DS by region [3]

The NEA and IEA roadmap also shows nuclear generation capacity variation from 2012 to 2050 in the 2DS by region (figure 5), during which the capacity of emerging countries, especially China, changes drastically. However, the capacity of OECD countries barely changes. Current reactors have been elaborated in developed countries for use in those countries. These countries should support developing countries in the use of nuclear energy. However, much safer, simpler and easier reactors are required for developing countries.

## 5. Innovative Nuclear Energy

### *5.1. Small Reactors (SRs)*

Soon after the TMI accident, many innovative reactor designs were proposed with inherent safety features, which depend not on the intervention of humans or electromechanical devices but instead on immutable and well-understood laws of physics and chemistry [11, 12]. These features are usually attained from favorable reactivity feedback for passive reactor shutdown, passive core cooling against decay heat, and superior confinement performance of radioactive materials. In general, SRs can perform these safety functions relatively easily [13].

**Table 2**. Small reactors (SRs) [8, 14–16]

| Name | Capacity | Type | Developer |
|---|---|---|---|
| CAREM | 27-100 MWe | PWR | CNEA + INVAP, Argentina |
| MRX | 30-100 MWe | PWR | JAERI, Japan |
| KLT-40S | 35 MWe | PWR | OKBM, Russia |
| NuScale | 45 MWe | PWR | NuScale Power + Fluor, USA |
| Flexblue | 50-250 MWe | PWR | Areva TA, France |
| SMART | 100 MWe | PWR | KAERI, South Korea |
| ACP100 | 100 MWe | PWR | CNNC + Guodian, China |
| NP-300 | 100-300 MWe | PWR | Areva TA, France |
| IRIS | 100-335 MWe | PWR | Westinghouse-led, international |
| CAP-150 | 150 MWe | PWR | SNERDI, China |
| mPower | 150-180 MWe | PWR | B&W + Bechtel, USA |
| SMR-160 | 160 MWe | PWR | Holtec, USA |
| Westinghouse SMR | 225 MWe | PWR | Westinghouse, USA |
| VK-300 | 300 MWe | BWR | Atomenergoproekt, Russia |
| PHWR-220 | 220 MWe | HWR | BARK, India |
| HTTR | 30 MWt | HTR | JAEA, Japan |
| PBMR | 165 MWe | HTR | Escom, South Africa, et al. |
| HTR-PM | 2x100 MWe | HTR | INET + HSNPC, China |
| SC-HTGR (Antares) | 250 MWe | HTR | Areva, France |
| GT-MHR | 285 MWe | HTR | GA + Minatom, USA-Russia |
| 4S | 10-50 MWe | FNR | Toshiba, Japan |
| SVBR | 10-100 MWe | FNR | AKME (Rosatom), Russia |
| Hyperion Power Module | 25 MWe | FNR | Hyperion Pwr Gen, USA |
| ENHS | 50 MWe | FNR | UCB, USA |
| LSPR, PBWFR | 50-150 MWe | FNR | TokyoTech, Japan |
| ALFRED | 120-600 MWe | FNR | Ansaldo, Italy |
| $EM^2$ | 240 MWe | FNR | GA, USA |
| BREST | 300 MWe | FNR | RDIPE, Russia |
| S-PRISM | 311 MWe | FNR | GE-Hitachi, USA |
| FUJI, miniFUJI | 10, 100-200 MWe | MSR | IThEMS, Japan-Russia-USA |
| IMSR | 45 MWe | MSR | Terrestrial Energy, USA |
| Mk1 PB-FHR | 100 MWe | FGR* | MIT + UCB + UWM, USA |
| Leadir-PS100 | 36 MWe | LGR** | Northern Nuclear, Canada |

*flibe cooled graphite moderated reactor, **lead cooled graphite moderated reactor

Now more than a half century has passed since Shippingport reactor started its operation, and the time is approaching of the replacement of many nuclear power reactors especially in USA. This situation was often called Nuclear Renaissance by nuclear promoters. The next generation of reactors is called Generation IV [17]. These reactors should satisfy very severe safety requirements. Especially after the Fukushima accident (Reactor type is BWR.), this requirement is inevitable. In these situations SRs are attracting strong interest. Many SRs are proposed now as shown in table 2 [8, 14-16]. Though many SR concepts are proposed, they are still in a R&D stage now. They hold a lot of merits, but they have a difficult problem of economy. The economy of these reactors is considered generally worse than the conventional large reactors because of their scale demerit. The mass-production in a factory may solve this problem.

Table 2 lists many types of SRs, especially for PWR, high-temperature reactor (HTR) and fast neutron reactor (FNR). Categorizing these by their generation, PWR, BWR and heavy water reactor (HWR) belong to Generation III and the others to Generation IV [17]. The Generation IV International Forum (GIF) was created in 2000. The GIF selected six systems as Generation IV technologies: gas-cooled fast reactor (GFR), lead-cooled fast reactor (LFR), molten salt reactor (MSR), sodium-cooled fast reactor (SFR), supercritical water-cooled reactor (SCWR), and very high-temperature reactor (VHTR). Using the type in table 2, VHTR belongs to HTR, and GFR, LFR and SFR to FNR. According to the GIF 2014 Technology Roadmap Update for Generation IV Nuclear Energy Systems [18], VHTR moved from the viability to performance phase in 2010, and SFR and LFR should do so by the end of 2015.

Technical feasibility of the SRs of PWR, BWR, HWR, HTR and some FNR (SFR and LFR) can be expected to be proven earlier. However, because of their scale disadvantages, the economy of these reactors is considered to be worse than conventional large reactors [18]. Means to overcome this obstruction are addressed in Section 6. The U.S. Energy Department is supporting R&D on SRs [19]. The IAEA is supporting long-term international activities regarding SRs.

The International Conference on Advances in Nuclear Science and Engineering was organized by Institut Teknologi Bandung. Then at the end of the session of SRs some topics about contribution of university to SRs R&Ds.

### *5.2. Breed-and-Burn Reactors (B&BRs)*

Safety and economy are only two of the five problems inherent to nuclear energy, as shown in figure 2. We should be concerned with the other three problems: resources, waste, and nuclear threats.

Another important reactor design concept for the future is the B&BR. The standing wave reactor (SWR), traveling wave reactor (TWR) [20] and CANDLE reactor [7] pertain to this concept. These reactors use only natural uranium, depleted uranium, and/or thorium for their fresh fuel, and do not require reprocessing. Therefore, they are free from the nuclear threat problem. The burnup of these reactors is very high, i.e., 20% for SWR and 40% for TWR and CANDLE. Therefore, they can use fissile materials very efficiently, and the amount of spent fuel per energy produced is very small. These performances provide excellent solutions to resource and waste problems.

B&BRs have the excellent features above, but also difficult technical problems. One is the material problem caused by their very high burnup, and the other is the difficulty of criticality performance. R&D on these reactors began recently in the USA and basic studies have initiated in several emerging countries.

### *5.3. Contributions by Universities*

The International Conference on Advances in Nuclear Science and Engineering was organized by Institut Teknologi Bandung. Then at the end of this Session of SRs some topics relating to universities are mentioned in the followings. In Japan the R&Ds of SRs are promoted by the international specialists' meeting SR/TIT organized by Tokyo Institute of Technology. The original idea of NuScale was born in Oregon State University, which is now running at the top of SRs development competition in the USA. And the concept of CANDLE was born in Tokyo Institute of Technology. Anyway, the nuclear energy was discovered by university professors. The contributions by universities to the innovative reactors should be large.

## 6. Roadmap

A technology roadmap of SRs and B&BRs is shown in figure. 6, together with conventional reactors.

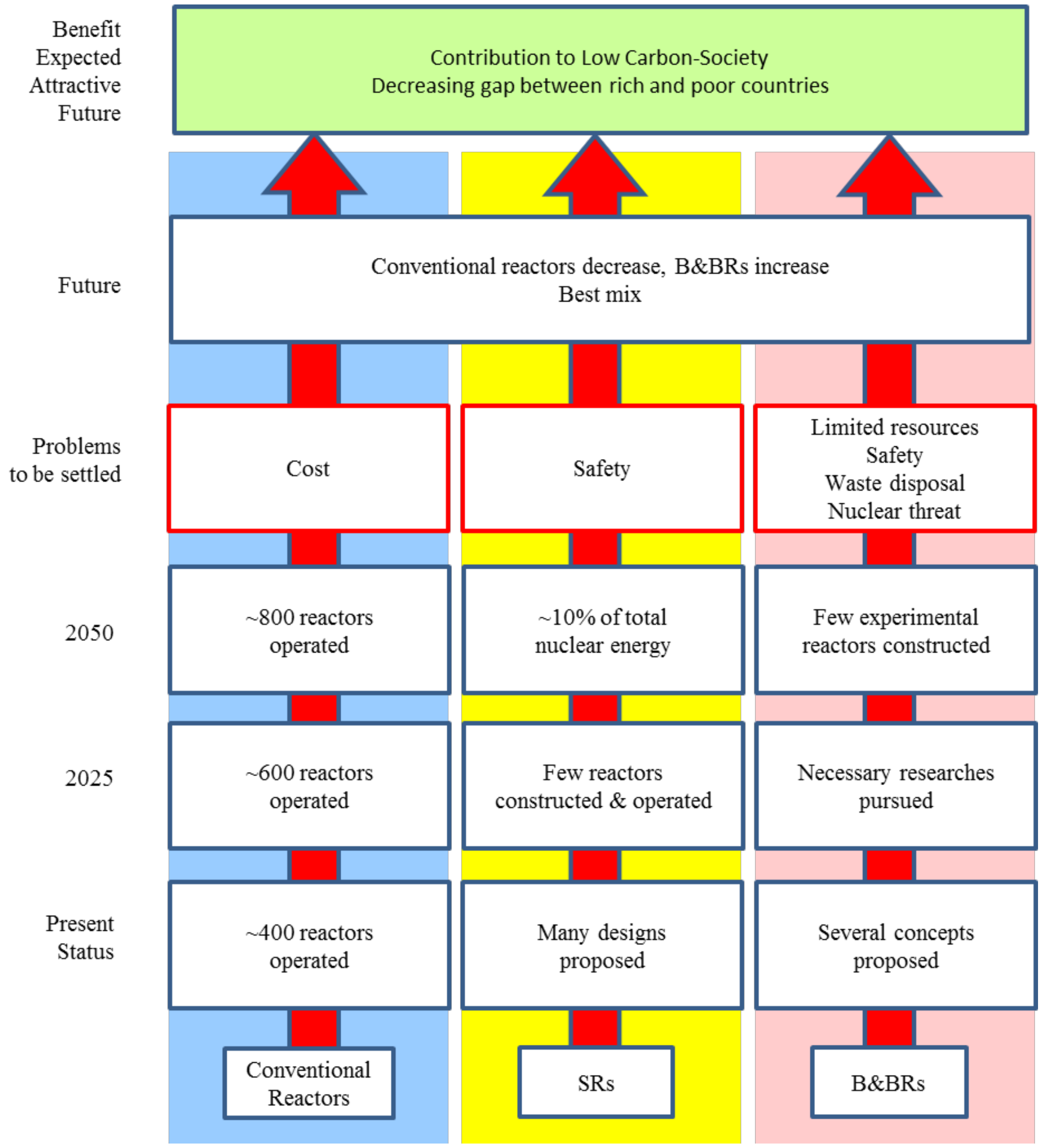


**Figure 6.** Technology roadmap of Japanese SRs and B&BRs, with predictions for conventional nuclear energy in Japan and forecasts of innovative nuclear energy in foreign countries (OECD countries, China, Russia and certain emerging countries).

The greatest obstruction to SRs is economics. However, we have many ideas to overcome this problem, including factory mass production [13]. SRs have many potential markets not accessible to large reactors. Further, they can be used in conventional large energy grids as modular reactors, demonstrating substantial advantages.
The major obstacle to B&BRs is technical, and is related to material development. It may take a long time to overcome this obstacle.

## 7. Benefit and Future Vision

Nuclear energy can considerably reduce greenhouse gas emissions and other environmental pollutants with acceptable cost. Daily control and maintenance of nuclear reactors are easily accomplished. However, as mentioned in Section 2, current nuclear energy has inherent and difficult problems to be solved at acceptable cost, i.e., limited resources, safety, waste disposal, and nuclear threats. The Fukushima accident has slowed nuclear reactor deployment, particularly in Japan. However, China [21] is aggressively promoting nuclear energy development. In many countries, these inherent problems are being studied more than before.

SRs will substantially solve the safety problem. B&BRs have great potential to solve all the inherent problems. SRs can realize special usages such as desalination, district heating, and certain industrial types. They can be used by ships and submarines, and are also expected to furnish undersea energy for investigation and mining. Many of these uses may be realized by the middle of this century. One additional important characteristic of nuclear energy is its very dense nature, as mentioned in Section 2. It needs no additional material like oxygen for fossil fuel. Therefore, it is almost the only useful energy for deep space, where in the far future, humans will attempt to penetrate. At that time, they will need nuclear energy. Nuclear reactors are currently producing considerable spent fuel waste. Most of this waste can be used as new nuclear fuel. Fissile concentration in the spent fuel of B&BRs is particularly high. Although presently only underground disposal is considered for nuclear waste, controlled storage should also be evaluated. In the future, transport to space may be much safer, cheaper and more reliable, if innovative techniques such as the space elevator [22] become available. At that time, storage of these wastes in artificial structures on/in the moon, asteroids, and outer space will become attractive options.

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