Energy Policy 38 (2010) 1962–1968

Contents lists available at ScienceDirect

Energy Policy

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

A 'must-go path' scenario for sustainable development and the role of nuclear energy in the 21st century

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ARTICLE INFO

Article history:
Received 5 May 2009
Received in revised form
25 November 2009
Accepted 25 November 2009
Available online 23 December 2009

Keywords:
Sustainable development
Energy resources
Fast reactor technology

ABSTRACT

An increase in the world population has accelerated the consumption of fossil fuels and deepened the pollution of global environment. As a result of these human activities, it is now difficult to clearly guarantee the sustainable future of humankind. An intuitional 'must-go path' scenario for the sustainable development of human civilization is proposed by extrapolating the human historical data over 30 years between 1970 and 2000. One of the most important parameters in order to realize the 'must-go path' scenario is the sustainability of energy without further pollution. In some countries an expanded use of nuclear energy is advantageous to increase sustainability, but fast reactor technology and closed fuel cycle have to be introduced to make it sustainable. In other countries, the development of cost-effective renewable energy, and the clean use of coal and oil are urgently needed to reduce pollution. The effect of fast nuclear reactor technology on sustainability as an option for near-term energy source is detailed in this paper. More cooperation between countries and worldwide collaboration coordinated by international organizations are essential to make the 'must-go path' scenario real in the upcoming 20 or 30 years.

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1. Introduction

It has been a long time since Sir Isaac Newton discovered the famous law of action–reaction in Principia Mathematica (Newton, 1687), which describes the phenomena of motion related to moving objects in nature. This principle is easily extended to be applicable to a closed system like the ecosystem on our planet. Therefore, it is natural that an external or internal perturbation applied to an ecosystem induces a kind of reaction or response to accommodate the applied action.

Humankind has become highly industrialized since the Industrial Revolution in the 18th century. This industrialization has been accelerated based on the energy extracted from fossil fuels such as oil, coal, and natural gas. However, the increased use of fossil fuels has deepened the pollution of the global environment, which has resulted in the increase of greenhouse gases (GHGs) in the atmosphere and distorted the balance of the energy flow in the Earth's system (Ramanathan, 1988). This is an unintended action on the Earth's system. Now, the accumulation of GHGs is said to be responsible for global warming which has caused an abrupt climate change and has had various influences on the ecosystem. This is a kind of reaction in the Earth's system. Recent studies by the World Energy Council (WEC) and also by the Intergovernmental Panel on Climate Change (IPCC) investigated the global warming problem and intensively analyzed the predictable influences on both human life and the ecosystem (WEC, 2007a; IPCC, 2007). The conclusion of these reports requires imminent action to solve these problems.

Even though there still remains some disagreement, many scientists now are alarming that the abrupt change of the global environment due to pollution (Risbey, 2008) and the variation of natural resources could threaten the sustainability of human life on the Earth. In other words, pollution and the depletion of natural resources could limit the sustainable development of our civilization. The concept of 'sustainable development' is well defined in the famous 'Brundtland Report' (UN, 1987) from the United Nations World Commission on Environment and Development (WCED). In this report, sustainable development is defined as "development that meets the needs of the present without compromising the ability of future generations to meet their need." Actually, sustainable development of modern civilization has been a controversial topic for more than 30 years since the future of humankind was simulated by a computer model called World3 described in the Club of Rome's report entitled "The Limits to Growth" (Meadows et al., 1972). The results predicted by the World3 model gave us two pessimistic future scenarios and an optimistic one.

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doi:10.1016/j.enpol.2009.11.077

More recently, Turner (2008) compared the three scenarios of 'Limits to Growth' with the true data of human history for the 30 years from 1970 to 2000. He suggested that modern civilization is on the trajectory of one of the projected pessimistic paths, which may result in a failure of sustainability in the mid-21st century. However, there is still the possibility of a successful sustainable development in the data of human locus provided by Turner (2008). Therefore, a 'must-go path' scenario is proposed which enables humankind to continue with sustainable development up to and beyond this century.

An ecosystem also seems to be governed by the law of inertia, which is another famous principle of motion described in Principia (Newton, 1687). From the viewpoint of inertia, the social system of humankind is the same as the ecosystem on earth. If the current dysfunctionality of these two systems is not changed, then the threat on the sustainable development of humankind will remain. Therefore, it is meaningful to derive some 'must-do' actions from the 'must-go path' on world population, food, pollution, natural resources, and others. The first change is expected from the pattern of energy production and consumption because the reduction of pollution may be the most urgent action. Therefore, a sustainable energy option deployable in the near-term was investigated.

2. Strategy for sustainable development

There are many criteria affecting sustainability. These factors revolve around human civilization; population change, food and water supply, energy supply, climate, pollution, and others. Among these criteria, the world population seems to be the most influential one directly affecting the sustainability of humans. An increase in population causes an increase in the use of natural resources, energy, food and other services. This trend is a natural one because people want to improve the welfare and the quality of their lives. However, the increased population causes the depletion of available resources, which results in a reduced birth rate due to limited services for a person and an increased death rate due to a deepening pollution. Thus, the population would decrease in turn.

It is straightforward that the simplest and most direct way to continue a sustainable development is to stabilize the world population at a reasonable level. However, it is unrealistic to control directly the birth rate and death rate in every part of the world because the population change itself is also affected by other factors of human civilization. To predict the future change of these complicated parameters, a scenario approach or probability approach is a useful modeling tool (van Vuuren et al., 2008).

2.1. A scenario to sustainable development

The World3 model used by Meadows et al. (1972) to develop the 'Limits to Growth' scenarios is a typical application of a scenario approach. In this study, the future of our civilization was predicted by modeling the interactions of five subsystems: population, food production, industrial production, pollution, and non-renewable energy resources. These subsystems were modeled to be inter-related linearly or not, and the change of one system and its feedback to other systems were also described in the model. For example, the change of population is determined by several parameters: health care, annual births and deaths, education, industrial production per capita, birth control program, etc. The change of population results in the change of population, industrial production, and natural resources. Three typical categories of scenarios were identified by the World3 modeling: two might result in significant collapse of civilization and one a stabilized development followed by a relatively mild collapse.

Turner (2008) gathered observed historical data on world population, services per capita, food per capita, industrial output per capita, non-renewable resources, and pollution from various databases covering the period between 1970 and 2000. He derived normalized indices on these parameters and compared the historical data with the output of the World3 simulation. The result implied that we are chasing the trajectory of one of the pessimistic scenario. The human historical data on population increase and industrial output per capita clearly correlate with the pessimistic prediction. The observed pollution data slightly deviates from the worst scenario. The real data on services per capita, food per capita, non-renewable resources are somewhere between the optimistic and the pessimistic scenarios.

Even the data obtained by Turner closely matched the results of simulation, which predicts the global collapse around the middle of the 21st century there is still the chance to shift the pattern of life to more sustainable development. Therefore, the 30 years of human historical data was extrapolated to obtain stabilization of parameters affecting sustainability and it was named as 'must-go path' scenario, which is the projection of expectations to a sustainable development of the modern civilization. The extrapolation is performed on the basis of the following:

- stabilization of sustainability parameters after the year of 2050;
- population increase by 25% till 2050 from that of the year 2000;
- increase in pollution by up to maximum value at 2050 and a gradual decrease thereafter.

In the 'must-go path' scenario the world population is stabilized without any remarkable increase of crude birth and death rates as illustrated in Fig. 1. The population change is closely related to other factors such as services per capita, food per capita, industrial output per capita, and also natural resources. Therefore, the stabilization of world population requires the stabilization of these factors of human life. To suggest the possibility of achievement of this population scenario the prediction results by the IMAGE 2.3 model (van Vuuren et al., 2008) are also described in Fig. 1.

The IMAGE 2.3 model takes into account the impacts of biofuels and carbon plantations on the long-term dynamics of global environmental change, i.e., land-use change, climate change, emissions of GHGs and air pollutants, energy use are

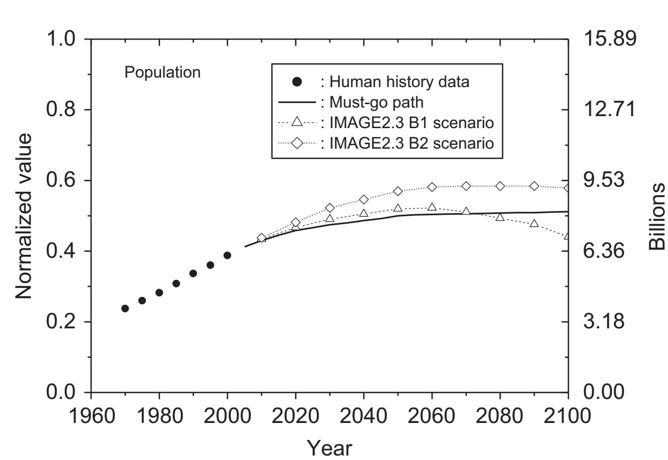

Fig. 1. Population data and its extrapolation to the 'must-go path' scenario.

modeled with related to the use of biofuels and carbon plantations in IMAGE 2.3. A simple climate model and a pattern-scaling method to project climate change at the grid level are included in IMAGE 2.3 (van Vuuren et al., 2007). The IMAGE 2.3 scenarios of B1 and B2 are predicted by taking the recent population changes and economic growth into consideration based on the B1 and B2 storylines of IPCC-SRES scenarios (IPCC, 2000), which have been derived based on the assumption of a global sustainable development and a regional sustainable development, respectively. It can be said that the 'must-go path' scenario is a more optimistic expectation than the predictions by the IMAGE 2.3 model.

As shown in Fig. 2 the food per capita, more specifically average supply per person of total energy content in food, is reasonable to be stabilized at a little bit higher output than the current level, which requires increased production rates, more effective distribution, and consumption patterns even at the increased level of population. The industrial output per capita illustrated in Fig. 3, which is in economic terms influenced by investments and depreciation, also has to be stabilized at a slightly higher value than the current level. This can only be definitely achieved when the industrial technologies are improved enough to compensate for the increase in world population.

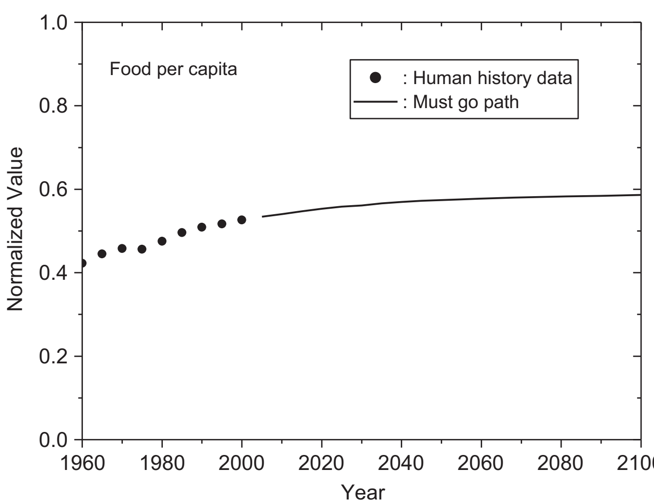

Fig. 2. Data on food per capita and its extrapolation to the 'must-go path' scenario.

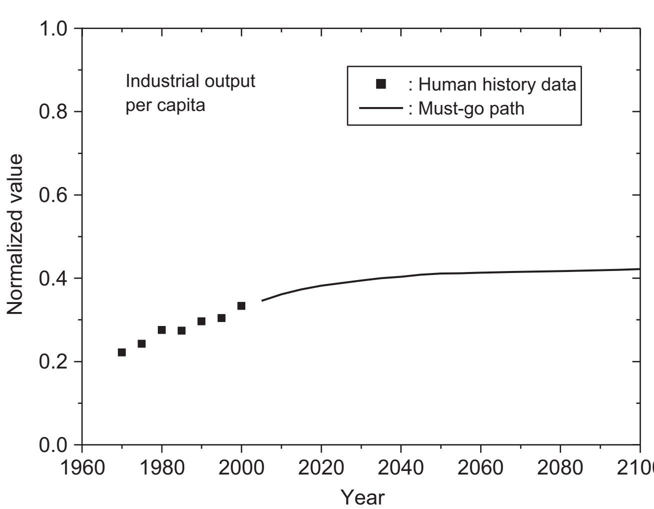

Fig. 3. Data on industrial output per capita and its extrapolation to the 'must-go path' scenario.

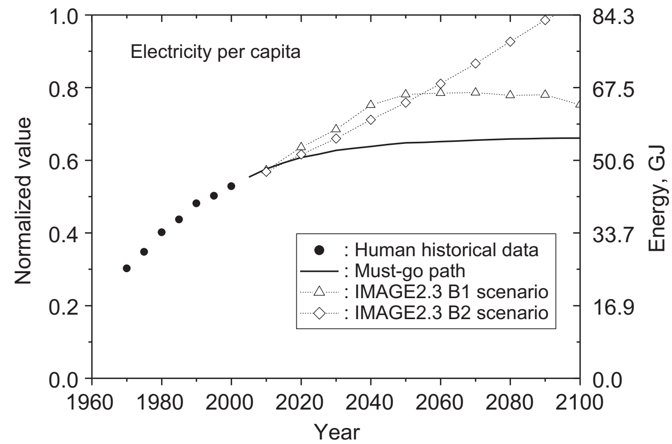

Fig. 4. Data on electricity per capita and its extrapolation to the 'must-go path' scenario.

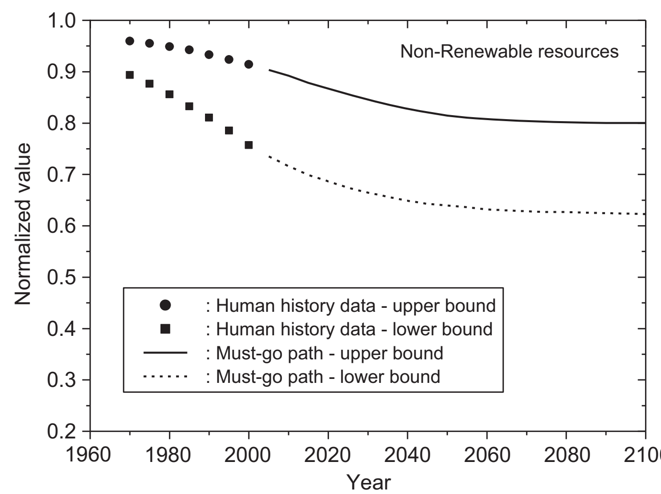

Fig. 5. Non-renewable energy resources remaining and its extrapolation to the 'must-go path' scenario.

Regarding the services per capita, it is reasonable to increase the electricity per capita slowly and stabilize it to an asymptotic value as shown in Fig. 4. This increase would be achievable by adopting a fast nuclear reactor technology and renewable energy sources. It has to be remembered that the IMAGE 2.3 prediction is for all the energy use not just for electricity. Therefore, as described by Fig. 4, the 'must-go path' scenario results in less electricity use than those predicted by IMAGE 2.3 model. This means a more effective energy use is important in order to realize the 'must-go path' scenario. Other services such as the literacy per capita have to be increased continuously to backup sustainable development worldwide. The 'must-go path' scenario requires the equitable sharing of food, industrial output and other services by all mankind on Earth.

The use of energy from non-renewable resources seems unavoidable until at least up to 2050 but has to be minimized before that and after this moment by utilizing fast nuclear reactor technology and by developing cost-effective renewable energy sources. A reasonable way of energy consumption from fossil resources is depicted in Fig. 5.

Worldwide efforts to control the pollution from fossil fuels are necessary for the achievement of the CO_2 targets in 2050. In the

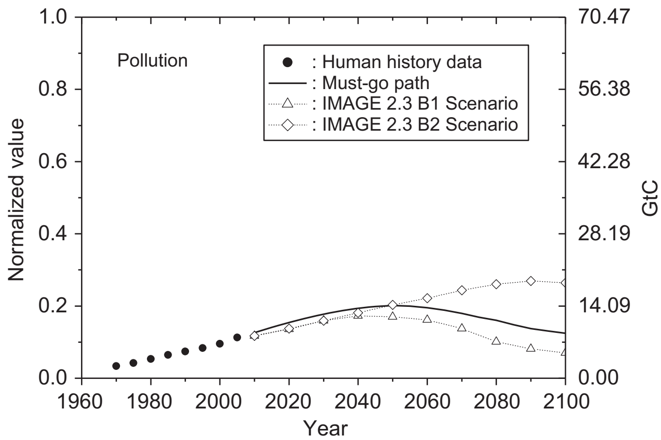

Fig. 6. Data on pollution and its extrapolation to the 'must-go path' scenario.

'must-go path' scenario it is assumed that the pollution, which is frequently expressed in tons of CO_2 equivalent, is successfully controlled by the launch of active anti-pollution policies and the change of energy consumption patterns before 2020, thus, it will reach its maximum level of pollution in 2050 and gradual decrease thereafter as described in Fig. 6. In this figure, the trends of energy use predicted by the IMAGE 2.3 B1 and B2 scenarios are also compared with the 'must-go path' scenario. It can be found that the 'must-go path' scenario results in very similar predictions with the B1 scenario.

2.2. Strategy to new era of sustainability

Sustainability, or non-sustainability inversely, is a function of various parameters correlated or tightly coupled each other, thus, it can be described as follows:

$$\text{Non-sustainability} = f\,(\text{population, services per capita, cost of services, pollution, material resources, non-renewable energy resources}). \quad (1)$$

If we borrow the Kaya identity, which is frequently used to define the emission (Raupach et al., 2007), the definition of non-sustainability can be formulated as follows:

$$\text{Non-sustainability} = \text{population} * \text{services per capita} * \text{cost of services} * \text{burden intensity of cost} \quad (2)$$

or

$$\text{Sustainability}^{-1} = \text{population} * \text{services per capita} * \text{cost of services} * \text{burden intensity of cost} \quad (3)$$

In the above expression, 'services' stand for any form of services which are required to increase the quality of human life. Therefore, 'cost of services' includes every form of costs to produce the service; natural resources, money, or environmental cost. Further, 'burden intensity of cost' means a relative measure for negative influence on environment and human civilization, which diminishes the sustainability of the present and the future generations. The non-sustainability before the Industrial Revolution can be defined as to be zero by assuming that the burden intensity at that time was zero.

For sustainable development, it is required to find a way to stabilize the world population with an increased level of human welfare not causing a remarkable depletion of non-renewable resources. The achievement of this goal in real life is a tough challenge requiring several changes in our daily lives and social systems.

A shift to a new era of energy is one of the most important and urgent changes for a sustainable development. If the current energy production and consumption patterns are maintained, the increase in world population would cause the depletion of non-renewable resources, which ultimately means the failure of sustainable development. Instead of it, if it is successful to utilize sustainable energy resources for human lives, it would be possible to improve the quality of human life without any remarkable threat even with an increase in world population. This shift to a sustainable energy scheme is a basis to decouple the social aspects of sustainability from physical aspects by removing the threat from pollution and depletion of natural resources. Highly sustainable energies can be obtained from renewable sources such as solar energy, wind energy, bio-energy, geo-thermal energy, etc.

The development of the green industry and green building is another important aspect for sustainability. Energy saving technologies are apparently able to improve the efficiency in energy use for lighting, heating, and others. An EU action plan adopted in 2006 aimed at promoting efficient energy technologies. The target of the plan was to reduce the EU's energy use by 20% compared to the projections for 2020 (WEC, 2007b). Systems for material recycling have to be prepared to support the green industry and the construction of green buildings. Heat and water supply for green industry will be provided by using a sustainable energy. If the sustainable energy is not sufficient, it would then be better to use natural gas or electricity for heating. It would be rather easy to expand the use of renewable energy for lighting. It might be advantageous to generate electricity from natural gas or a nuclear source until the renewable energies become fully developed, which is believed to reduce the pollution.

On the transportation side, the development and wider use of carbon-free vehicle (CFV) would highly increase the sustainability of our civilization. It is required to enhance the energy efficiency of a CFV, thus, make it cost-competitive to fossil-fueled vehicles (WEC, 2007a). To have a matured fuel cell is a core technology for CFV. The energy for fuel cell would be supplied from natural gas or from nuclear plants. It should be remembered that a vehicle fueled with hydrogen from natural gas is not fully carbon-free if the carbon from natural gas is not captured in the production of hydrogen. If the technology for carbon sequestration from biomass became efficient, hydrogen generated from biomass would be the primary energy for fuel cells (Azar et al., 2003).

In developing countries or poor countries, however, a threat may come directly from the population itself, or food and water supply. Therefore, it would take much more time to shift the energy scheme and to apply the technologies for green industry and green building. It is important to develop and implement the policies for population stabilization in these countries through the cooperation with international organizations. Support to raise and maintain international education system is essential because it increases the literacy rate, which helps the implementation of the required policies. The development of technologies for energy saving and high energy efficiency for the clean consumption of coal and oil is more urgent for developing countries.

3. Nuclear energy of sustainability

As described previously, one of the key parameters for the realization of the 'must-go path' is to prevent non-renewable energy resources from being depleted drastically. For this to happen, it is important to minimize the energy consumption by increasing the efficiency of energy use. The development of various energy saving technologies is highly recommended. More important aspect for the conservation of non-renewable resources is the shift of current energy sources to sustainable energies and thereby not causing further pollution. The use of renewable energy, especially solar energy which is almost absolutely renewable, is the best one. However, economic systems and industries for the wide use of renewable energy are not yet well prepared mainly because renewable energy is usually weather dependent and uncontrollable (Omer, 2008). Therefore, for the time before the renewable energy becomes efficient as a meaningful energy source for the current civilization it seems advantageous to continue the use of nuclear energy, which supplies relatively clean energy when it is compared to the energies from fossil fuels. It means that the role of nuclear energy is essential in the early 21st century. As summarized in the WEC report (WEC, 2007a) the extended use of nuclear energy in the 21st century is still controversial because of worries about safety, waste management, decommissioning, and links with military programs. In the beginning of sustainable energy development, however, nuclear energy might play the role of supplying stable and high-quality electricity with minimized pollution in several developed and developing countries.

Actually, the nuclear energy from current nuclear power plants, which produce energy from fission of the uranium, cannot be said to be sustainable because the uranium resource is also limited and it unavoidably accumulates the spent fuel which is highly radioactive, thus, problematic to future generations. However, the energy from fast nuclear reactor technology is estimated to be highly sustainable because it does not induce further burden to the environment. On the contrary, it mitigates the burden by utilizing the spent fuel of the current nuclear power plants and also by completing a closed fuel cycle, which means the resource is not limited for several centuries.

Many countries are well-aware of the importance of developing a sustainable fast nuclear reactor technology in the coming 20 years. Recently, ten countries have joined up to form the Generation IV International Forum (GIF) to develop future nuclear energy systems satisfying the goals of sustainability, economics, safety and reliability, proliferation resistance and physical protection. Through extensive investigation and debate the GIF selected six Generation IV (Gen IV) nuclear energy systems, which included three fast reactor systems of gas-cooled fast reactor

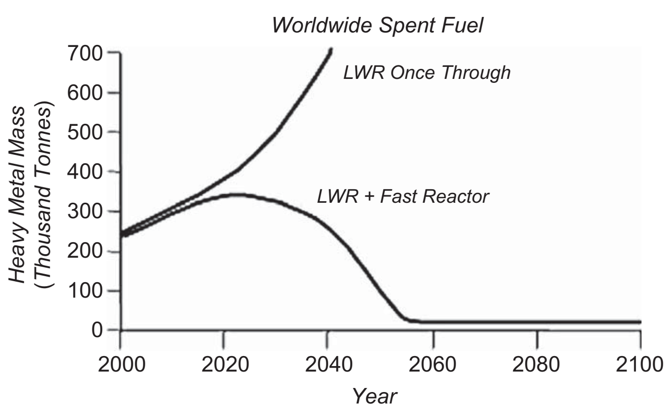

Fig. 7. Trend of worldwide spent fuel depending on fuel cycle strategies (GIF, 2002).

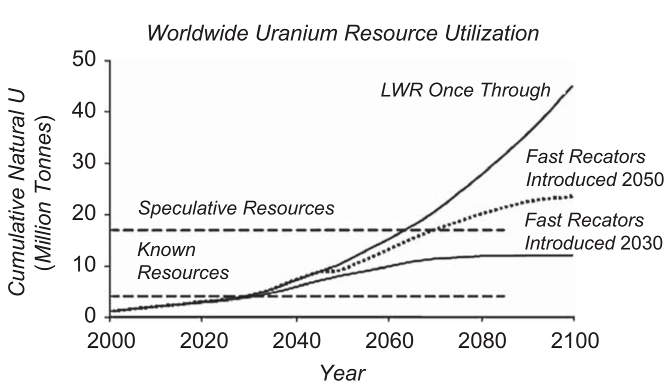

Fig. 8. Trend of worldwide uranium resource depending on fuel cycle strategies (GIF, 2002).

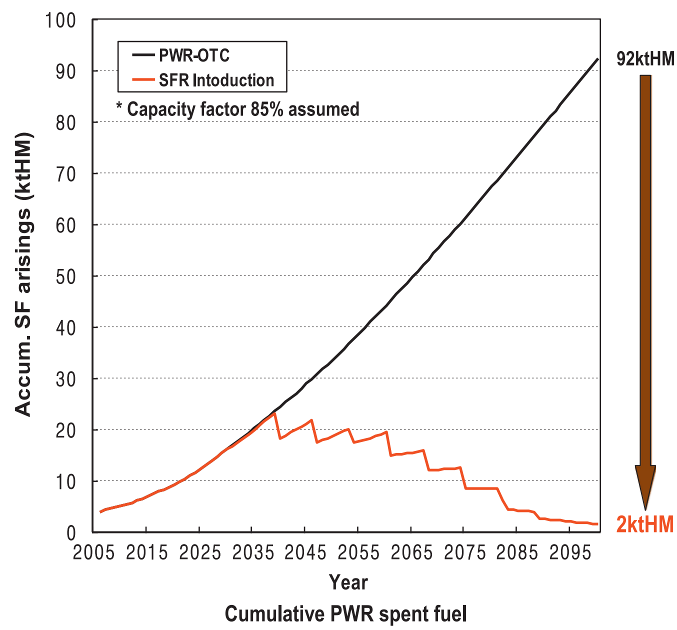

Fig. 9. Effect of SFR deployment on cumulative PWR spent fuel in Korea.

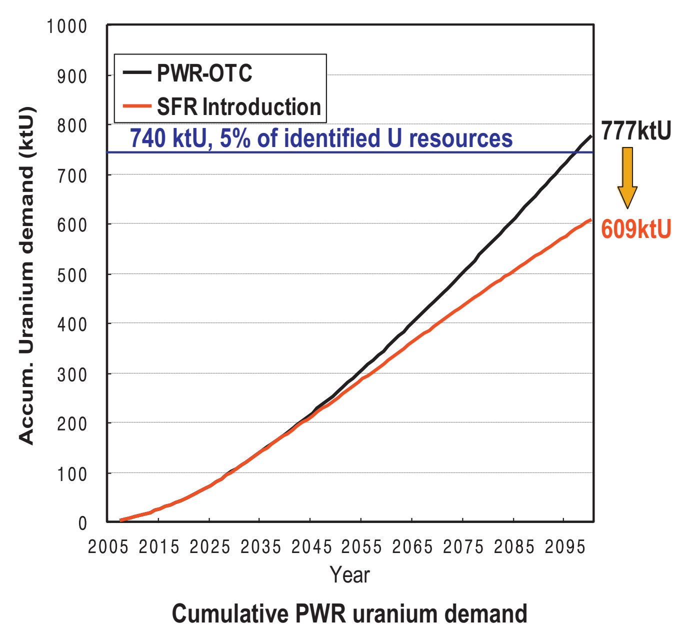

Fig. 10. Effect of SFR deployment on cumulative uranium demand in Korea.

(GFR) system, lead-cooled fast reactor (LFR) system, and sodium-cooled fast reactor (SFR) system (GIF, 2002). To check whether a future nuclear system is sustainable or not, the GIF used three criteria of sustainability; fuel utilization, waste minimization, and environmental impact of waste management and disposal.

One of the goals to develop a fast reactor system is the completion of a closed fuel cycle for efficient conversion of fertile uranium and management of actinides. The reference reactor for GFR is a helium-cooled system operating with an outlet temperature of 850 °C using a direct Brayton cycle gas turbine for high thermal efficiency. The on-site fuel cycle facilities can minimize transportation of nuclear materials and will be based on either advanced aqueous, pyrometallurgical, or other dry processing options. The LFR system uses a lead or lead/bismuth eutectic liquid-metal coolant. Options for an LFR include a nuclear battery of 50–150 MWe that features a very long refueling interval, a modular system rated at 300–400 MWe, and a large monolithic plant option at 1200 MWe. The fuel of LFR is metal or nitride-based, containing fertile uranium and transuranics. Regarding the SFR system a full actinide recycle fuel cycle is envisioned with two major options: One is an intermediate size (150–500 MWe) sodium-cooled reactor with a uranium–plutonium–minor actinide–zirconium metal alloy fuel, supported by a fuel cycle based on pyrometallurgical processing in collocated facilities. The second is a medium to large (500–1500 MWe) sodium-cooled fast reactor with mixed uranium–plutonium oxide fuel, supported by a fuel cycle based upon advanced aqueous processing at a central location serving a number of reactors.

The other three Gen IV nuclear energy systems are molten salt reactor (MSR) system, supercritical-water-cooled reactor (SCWR) system, and very-high-temperature reactor (VHTR) system. The MSR system utilizes an epithermal to thermal neutron spectrum and a closed fuel cycle for an efficient utilization of plutonium and minor actinides. The fuel for MSR is a liquid mixture of sodium, zirconium, and uranium fluorides circulating graphite core channels. The SCWR features a high thermal efficiency approaching 44% achieved by using a high-temperature, high-pressure, water-cooled reactor that operates above the thermodynamic critical point of water (22.1 MPa, 374 °C). The VHTR aims at faster deployment for the high temperature process heat applications, such as coal gasification and thermo-chemical hydrogen production, with superior efficiency. It utilizes a thermal neutron spectrum and a once-through uranium cycle.

A GIF study found that the once-through fuel cycle being currently used can cause limitation of repository space and also make uranium resource availability a limiting factor as illustrated in Figs. 7 and 8. The same figures also suggest that the completion of a fully closed fuel cycle combined with fast reactor systems can reduce the residual wastes and allow a more efficient utilization of uranium resource.

A prediction of nuclear waste specifically to the Republic of Korea (Kim et al., 2008) is shown in Fig. 9. This prediction is based on the assumption that the operation of commercial SFRs will be started in 2040 with the capacity factor of 85%. If the once-through fuel cycle is maintained, it is predicted that 92 kt of spent fuel from pressurized water reactors (PWRs) will be accumulated till the end of the 21st century. On the other hand, the deployment of SFRs before the middle of 21st century will reduce the cumulative PWR spent fuel by 98% at the end of this century. The deployment of SFRs will also be advantageous in the viewpoint of sustainability by reducing uranium demand as described in Fig. 10. SFRs will support nuclear waste minimization and fuel utilization efforts, thus contributing to a sustainable development in the Republic of Korea.

One of the obstacles to fast reactor deployment has been economics of the systems. Recently, design innovation enhanced the economic competitiveness of fast reactors to the conventional type of reactors. Fig. 11 suggests that the economics of recent SFR designs is approaching that of typical PWR, APR-1400 in Fig. 11. It should be remembered that a fast reactor system still has the problem of disposal of low level radioactive wastes and other problems like public acceptance, etc. Therefore, a deployment of fast reactor system requires a balanced view of economics, sustainability, and social cultures.

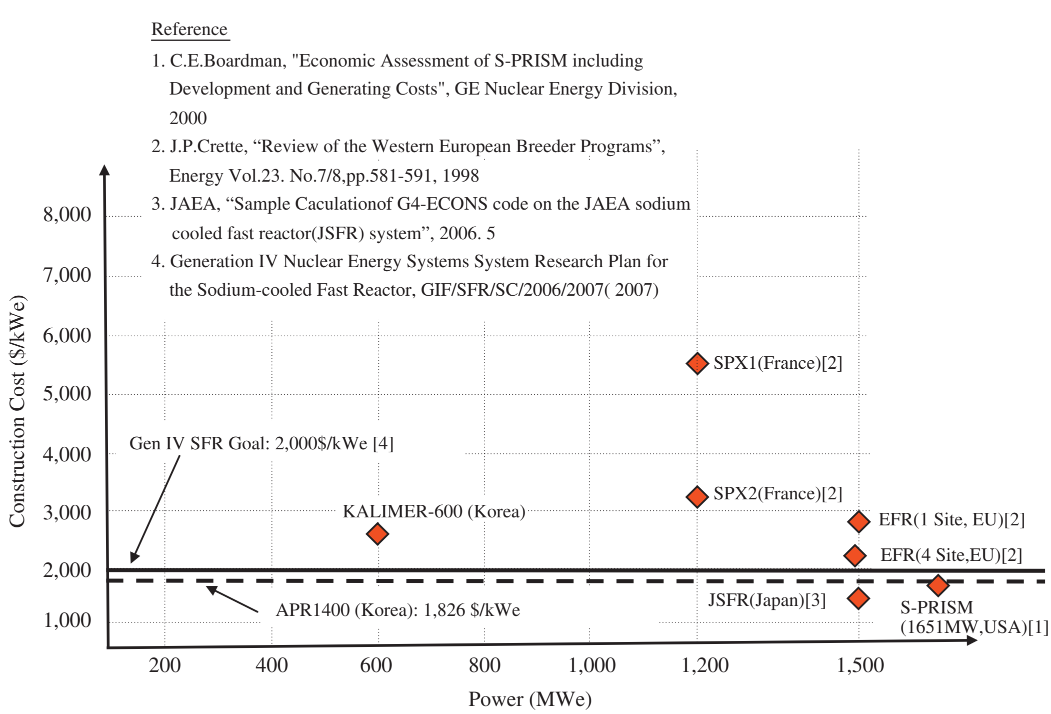

Fig. 11. Comparison of estimated construction costs for SFRs.

4. Conclusions

It is evident that one of the most urgent problems to mankind in the 21st century is sustainable development. A 'must-go path' scenario for future sustainability is proposed by extrapolating the human history data for the last three decades. Minimizing the use of non-renewable energy resources without further pollution is a key factor to realize the 'must-go path'. In the 'must-go path' scenario, it is assumed that the stabilization of food, services, and population can be reached by supplying enough energy to humankind from the fast nuclear reactor technology and by developing cost-effective renewable energies.

The following policies are recommended to the developed and developing countries and also to the international organizations:

- For the countries with mature nuclear technologies it is advantageous to deploy fast reactor systems and complete a closed fuel cycle, which will contribute to an increased energy sustainability.
- The development of technology on efficient energy use and energy saving has to be promoted and supported by governments and society.
- International organizations have to prepare active plans, which encourage more collaboration and transfer of technologies on renewable energy development and carbon sequestration between countries.

For breaking the inertia of a moving system, it is required to exert an appropriate opposing force on the system. The bigger the system, the more the work required. Human society and the ecosystem surrounding it are two big systems influenced by each other. It is time for humankind to exert much effort on these systems to change their inertia to another direction towards sustainable development. The work of 'must-do' action would be painful but it is our 'must-go path'. Worldwide efforts are required to achieve sustainable development by following the 'must-go path' scenario.

Acknowledgement

This work has been performed under the Long-term Nuclear R&D Programs supported by Ministry of Education, Science and Technology (MEST), Republic of Korea.

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