



Article Effects of Nuclear Energy on Sustainable Development and Energy Security: Sodium-Cooled Fast Reactor Case

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Abstract: We propose a stepwise method of selecting appropriate indicators to measure effects of a specific nuclear energy option on sustainable development and energy security, and also to compare an energy option with another. Focusing on the sodium-cooled fast reactor, one of the highlighted Generation IV reactors, we measure and compare its effects with the standard pressurized water reactor-based nuclear power, and then with coal power. Collecting 36 indicators, five experts select seven key indicators to meet data availability, nuclear energy relevancy, comparability among energy options, and fit with Korean energy policy objectives. The results show that sodium-cooled fast reactors is a better alternative than existing nuclear power as well as coal electricity generation across social, economic and environmental dimensions. Our method makes comparison between energy alternatives easier, thereby clarifying consequences of different energy policy decisions.

Keywords: sustainable development; energy security; sodium-cooled fast reactor; nuclear energy; coal electricity generation

1. Introduction

Sustainable development is defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs [1]. It has no single, clear definition, but addresses numerous social, economic and environmental issues including poverty, impoverishment of the environment, disasters and others [2]. Energy has been one of keys to economic development as well as improved social well-being. However, along all energy value chains from resource extraction to use, pollutants are produced, emitted and disposed of, thereby creating environmental damages. Thus, energy is crucial to achieving sustainable development because it has social, economic and environmental effects on sustainability as well as economic development.

Considering this, the International Atomic Energy Agency (IAEA) developed a set of energy indicators for sustainable development at a national level [3]. Measuring the current status of energy issues for sustainable development, it was expected to guide policymakers to suitable energy policies. In addition, it is a tool of monitoring consequences by different policy choices. IAEA has disseminated indicators over many countries while working closely with the United National Department of Economic and Social Affairs, the International Energy Agency (IEA), and the European Environment Agency.

As noted by von Hippel et al., the IAEA energy indicators for sustainable development touch upon similar issues and perspectives of energy security [4]. Traditionally, energy security was defined as security of access to oil and other fossil fuels [5]. It was a narrow supply-oriented definition, but enough to identify and manage major energy risks at a national level. However, increasing complexity of recent energy landscape creates new risks and challenges from environmental, technological, energy demand, socio-cultural, international relation and military sectors [4,6]. Addressing these issues, new energy security concept becomes more comprehensive, and has many overlaps with the concept of sustainable development.

Consequently, national energy policies seek ways of enhancing sustainable development as well as energy security [7]. Governments, international institutes and researchers make efforts to define new comprehensive concepts, and further to develop indicators of measuring qualitative and quantitative factors in multi-attributes [7–9]. In responsive to such needs, many indicators are developed to clearly show overall status of energy equity, use, import, and environmental quality at a national level. Economic indicators focus on fossil fuels and their effects because of their high shares in the energy supply. Differently, environmental indicators emphasize contrasting effects between fossil fuel and renewable energy.

Nuclear energy has established itself as a key energy supply option in some countries including France, Russia, China, India and others [10]. Despite stronger public oppositions to nuclear energy after Fukushima accident, these countries remain committed to continuous nuclear power expansion plans with stringent safety systems. There has been a continuous debate on acceptability and appropriateness of nuclear energy, but has little effort to measure its effects on energy security as well as sustainable development. This is mainly due to multi-faceted and often contrasting effects of nuclear energy. For instance, it has advantages of lower greenhouse gas emissions in an environmental sustainability aspect, but could have negative impacts in terms of potential environmental contamination and long-time radioactive hazard.

Tackling this issue, we suggest a method of measuring effects of nuclear energy on sustainable development and energy security at a national level, and further of comparing its effects against other nuclear energy options and different energy sources. Reviewing existing indicators of sustainable development and energy security, we select appropriate indicators in a specific national energy policy context. These indicators are used to anticipate future effects of nuclear energy options against other existing as well as future energy alternatives.

Korea is a typical of countries expanding nuclear programs under similar debates, and is therefore appropriate to demonstrate our method. One of the highlighted next-generation nuclear energy options in Korea is the sodium-cooled fast reactor (SFR). We compare its effects with the standard pressurized water reactor (PWR), which constitute the large majority of existing nuclear power plants, and then with the coal power generation. Fossil fuel plants provide 65.4% of Korea's total electricity production in 2015. Coal electricity generation accounts for more than 95% of fossil fuel generation capacity as well as electricity production. It is therefore the most suitable for comparison between existing main and new energy alternatives.

The rest of this paper is organized as follows. In Section 2, we review concepts and indicators of sustainable development and energy security. Backgrounds of nuclear energy and SFR are briefly introduced, including technological, environmental and economic advantages and disadvantages. Section 3 presents the research framework and methodology. Subsequently, empirical analytic results are provided in Section 4. We end with some discussions and conclusions.

2. Literature review

2.1. Sustainability, Sustainable Development and Energy Security

Sustainability is defined as a sustainable process or condition that can be maintained indefinitely without progressive diminution of valued quantities [11]. From a social perspective, United Nations

World Commission on Environment and Development (UNWCED) combines sustainability with development, and suggests the definition of sustainable development as noted previously [1]. This definition has been widely used mainly due to its intuitive appeal, but has been criticized because it is difficult to operationalize and implement. It leads to a plethora of different definitions of sustainability as well as sustainable development [12].

In order to make concepts more specific, some existing research gives structure to a wide array of issues associated with sustainable development. Key issues are endangered human survival, oppression of human rights, reduced quality of life, and impoverishment of environment [7,13,14]. Some forces drive these issues, including excessive population growth, misuse of technology, poor distribution of consumption and investment and others. Despite arguments for and against issues and forces, there is a perception that sustainable development is hampered by a lack of knowledge about past, present and future of the world [4]. In other words, it is important to understand the state of the world, and further to measure the effects of human actions on humanity and environment [14].

Any human action affecting key issues of sustainable development needs energy. It means that a sustainable economy should produce more output with less energy and environmental risk. Key sustainable development issues composed of human survival, quality of life and environmental risk could be improved by stable, efficient, safe and environment-friendly energy production and use. These are objectives of national energy policies across countries, and are also important factors of national energy security. A country can greatly move toward a sustainable economy by overcoming energy security challenges such as shift from fossil fuels to renewable energies [4,15].

Energy security has many different existing definitions. However, it is notable that the concept has also widened to include energy supply, price volatility, political stability, energy efficiency and others [16,17]. Recent studies continuously add new factors, including geopolitical conditions, government control of energy resources and national policy time horizon [4,6,8]. It is increasingly becoming comprehensive, thereby covering broad social, economic and environmental aspects. In addition, it considers more and more country-wise conditional differences. Energy security concept is moving toward broader coverage and customization to different national conditions because countries share some common as well as different characteristics and conditions [4]. Another thing to note is that more comprehensive energy security concepts have many overlaps with concepts of sustainability and sustainable development.

Considering this, researchers suggest broad characterization of the above-mentioned concepts. They identify key components of three concepts while clarifying overlaps between concepts. Consequently, conceptual scope and boundary become clearer than as those were. However, concept alone is not enough to manage energy security as well as sustainable development in practice. There are three practical issues ahead: (1) development of indicators to measure key dimensions; (2) selection of suitable indicators in the national energy context; and (3) design of a workable analytic framework for evaluation or comparison of different energy policies. Addressing the second and third issues, our research is an effort to create a link from a set of suitable indicators to comparison of possible energy options.

2.2. Nuclear Energy and Sodium-Cooled Fast Reactor

Global energy demand has continuously been rising, and will show strong growth. A challenge is to keep balances between supply and demand. In addition, it is a must to fight against environmental pollution. Governments therefore have to find solutions of producing more energy with fewer emissions, but have difficulty in finding the best energy mix because of different advantages and disadvantages of several energy sources. Renewable energies can significantly reduce emissions, but some renewable energy sources suffer from high unit cost of electricity and limited availability. Fossil fuels have economic advantages, but are not free from severe and irreversible environmental damages. Nuclear energy has advantages of less air pollution, low cost and stable energy supply on a large scale. Its considerable share in the global energy mix is due to these advantages. However, it is not easy to justify nuclear energy choices because of critical risks including fatal accident and radioactive wastes. In order to reduce risks, governments have kept on making investment for safety system and new wastes disposal methods.

Since the 1970s, the second-generation PWR has continuously increased its share in the nuclear market, and dominates the commercial market of nuclear power reactors [18]. The third-generation reactor improves the operational life more than 20 years while reducing core damage frequencies by 94%, but have not many have been built, even in developed countries [19]. Initiated in 2000, the fourth-generation reactors are at the research stage, and will be commercially available somewhere between 2030 and 2040. Most currently functioning reactors are PWRs, and are expected to be gradually replaced by the third- or fourth-generation reactors. For instance, Brinton and Tokuhiro estimated that 50–75 nuclear power plants would be newly deployed in US [20].

The Fukushima accident emphasizes importance of the highest level of safety and reliability. In addition, there is a consensus that nuclear energy should meet increasing electricity demands on a sustainable basis. Closing of the nuclear fuel cycle including reprocessing, partitioning and reuse of spent nuclear fuel is therefore regarded as an important component to achieve the sustainability goal [21]. Improved nuclear fuel cycle technologies have been developed, including the process of capturing krypton and xenon [22,23]. Last but not least, economic competitiveness is of great importance.

Considering this, the Generation IV International Forum (GIF) created nearly 100 concepts as the Generation IV (GEN-IV) reactors, and selected six promising systems: (1) gas-cooled fast reactor (GFR); (2) lead-cooled fast reactor (LFR); (3) molten salt reactor (MSR); (4) sodium-cooled fast reactor (SFR); (5) supercritical-water-cooled reactor (SCWR); and (6) very-high-temperature reactor (VHTR) [24]. Six systems have the potential to meet key criteria: (1) safety and reliability; (2) economics; (3) sustainability; and (4) proliferation resistance and physical protection [25]. In terms of the fuel cycle, the transition from the open fuel cycle to more optimized closed cycle is crucial to achieve the sustainability goal [26]. Thirteen countries including France, Japan, China and Korea are members of this forum, and have been developing technologies and associated designs of six systems.

Each system has its own advantages and challenges. SCWR has advantages of lower operating cost due to high thermal efficiency and simple design, but need to improve safety and physical protection in terms of core power stability and reactor material selection [27]. MSR has unique safety features including lower fissile inventory, lower radiation damage and others with efficient use of fuels. However, several challenges including robust processing of highly radioactive salt mixture and corrosion of circuit components remain unsolved [27]. LFR has low capital cost due to simple design, and also efficiently utilizes neutron and uranium [28]. Disadvantages are mainly due to the dense, corrosive and erosive nature of the lead, including higher pumping power and safety problem. Similarly, the use of a gas coolant in the GFR has advantages of chemical stability, easy inspection, less risk of accident and others, but also has disadvantages of higher pumping power, risk of vibration and difficulty in extracting the decay heat [29]. VHTR can generate electricity with high efficiency and early deployment. The use of a gas coolant in the VHTR has same challenges with the GFR although its lower power density substantially softens those issues.

SFR has advantages of little corrosion and reduced capital cost. In addition, it can make best use of limited nuclear fuel resources, and manage nuclear wastes by closing the fuel cycle. Further, SFR technology is mature more than other GEN-IV systems [26]. Despite advantages, SFR has technological challenges including assurance of passive safety response and evaluation of bounding events. Focusing on its commercial viability in the near future, some countries with high uranium import dependence have a favor to SFR. Korea is a typical country of planning to replace some PWR by SFR. However, it is difficult to measure effects of different nuclear energy options on sustainable development and national energy security. Further, the development of symbiotic cycles to take advantages of different systems makes comparison more difficult [30,31].

3. Methodology

3.1. Research Framework

Our method must address three issues: (1) identification of key indicators to measure effects of nuclear energy options on sustainable development and energy security in the specific national energy policy context; (2) comparison of a nuclear energy option with another nuclear option; and (3) comparison of a nuclear energy option with a conventional energy source.

As shown in Figure 1, through a broad review of existing literature, we create a comprehensive pool of indicators. These indicators proceed through two stages of appropriateness evaluation. At first, criteria of data availability, relevance to nuclear energy and comparability are used for selection. Then, we assess the fit of indicators to the key national energy policy objectives. Five experts are involved in these processes, thereby identifying key nuclear energy indicators customized to the Korean energy policy context. They are composed of a policymaker, a nuclear energy researcher, an economist, an industry expert of environmental technologies, and a professor of environment and energy. A coordinator with boundary-spanning backgrounds in nuclear energy research, economics and policy guides them into iterative divergent-convergent thinking. A structured brainstorming is used to reduce subjective biases and negative effects of interactions among experts. It consists of four phases: (1) problem statement; (2) individual idea generation; (3) collective organization of ideas; and (4) collective evaluation and selection [32]. It separates individual idea generation (divergent thinking) from collective evaluation (convergent thinking), thereby reducing negative effects including subjective bias and bandwagon effect. However, it should be noted that some biases remain.



Figure 1. Overall research framework.

Using selected indicators, we measure the effects of SFR (future nuclear power option), and compare its effects with those of PWR (current nuclear power option) and coal electricity generation (current main power option). Over key dimensions of sustainable development and energy security, advantages and disadvantages of SFR against PWR and coal electricity generation become clear. Comparisons between different energy options become easy, and therefore helps policymakers as well as researchers identify the best energy option with its future consequences.

3.2. Key Indicators for Sustainable Development and Energy Security

A number of indicators have been suggested for either sustainable development or energy security, and often for both. Our experts identify the five suitable indicators for the Korean nuclear energy policy context including nuclear accident cost, reserves-to-production ratio (RPR), net energy import dependency (NEID), energy security index price component indicator (ESI_{price}), and cost of solid radioactive wastes disposal [9,13,33,34].

Nuclear accident cost is composed of six categories: (1) lost reactors; (2) lost power; (3) fatal cancers; (4) lost agricultural production; (5) displaced populations; and (6) cleanup [34].

Nuclear accident cost =
$$\frac{\alpha r + \beta pr + \sum_{i} \gamma_{k} + \delta AL + \varepsilon DP}{(1+i)^{t}}$$
(1)

where α denotes the coefficient of loss per reactor, and r is the capacity of lost reactors in a power plant. An average cost of lost power per hour β is multiplied by annual running hour p and capacity r. It resulted in the total cost of lost power. The cost of fatal cancer is γ_k for an individual patient k. Total cost of fatal cancers can be calculated by summing up costs for all patients The coefficient δ denotes the annual cost of agricultural loss per km² with the area lost for agricultural production (AL). Finally, the average cost per displaced person is ε , and the number of displaced persons is DP. Uncertainty is too high to estimate cost of cleanup because it will occur over the long term. It therefore is not considered for comparison. An accident in year t is discounted by a factor $(1 + i)^{t}$.

RPR is defined as the ratio of lifetime of proven energy reserves to the production life index [13]. It can be formulated as follows.

$$RPR = \frac{AR}{AP}$$
(2)

where AR denotes the amount of an energy resource known to exist, and AP the amount of resource produced in one year at the current rate. RPR is used to estimate future energy supplies with respect to current availability of energy reserves and levels of production. It is a typical indicator of energy availability.

NEID is a refined import dependency indicator. Asia Pacific Energy Research Centre (APERC) combines measures of not only import dependence but diversity by modifying the Shannon Index as follows [13].

$$NEID = \frac{\sum_{i} m_{i} p_{i} ln p_{i}}{\sum_{i} p_{i} ln p_{i}}$$
(3)

where m_i the share in net imports of energy carrier i, and p_i its share in total primary energy supply (TPES). More diversified energy imports as well as energy sources result in higher NEID, implying higher security of energy supply.

ESI_{price} measures the exposure of individual countries to energy security risks due to international energy market structure and the degree of the country's energy resource diversification [9].

$$ESI_{price} = \sum_{f} [ESMC_{pol-f} (C_{f} / TPES)]$$
(4)

where TPES denotes the total primary energy supply of all fuels and C_f is the total supply of the fuel f for the country. ESMC_{pol-f} stands for the measure of energy security market concentration for the fuel f, and can be formulated as follows. ESI_{price} could measure the degree of exposure to total energy price risks for all fuels in the country.

$$ESMC_{pol} = \sum_{j} \left(r_{j} S_{jf}^{2} \right)$$
(5)

where r_i is the political risk of the supplier country j for the fuel f, and S_{jf} is the share of the supplier country j in the international market of the fuel f. Higher $ESMC_{pol}$ can be translated into higher market concentration, implying the low level of energy security due to the risk of price volatility.

Disposal cost of solid radioactive wastes is useful to compare different nuclear energy options, and also can be used to compare different energy options in terms of emission cost.

$$C_{SRW} = \alpha UPWR + \beta UHSFR$$
(6)

where α is the cost of used PWR fuel wastes disposal per kilogram, and β is the cost of used SFR high-level radioactive wastes disposal per kilogram. The unit of measurement for the amounts of PWR wastes (UPWR) and SFR high-level wastes (UHSFR) is kilogram.

3.3. Data Collection

We collect global energy data mainly from IAEA and Organisation for Economic Co-operation and Development (OECD) IEA [35,36]. For some missing data, we use reports and documents by BP (British Petroleum) and APERC [37,38]. Same data from different sources are cross-checked to eliminate inconsistent data. Korean power statistics are collected mainly from Electric Power Statistics Information System including power generation capacity, annual electricity generation and others [39]. Using Korea Energy Statistics Information System, we collect general national-level energy data including TPES and energy import [40]. For detailed nuclear energy information, data from Korea Atomic Industrial Forum are used [41]. When some inconsistency is found between databases, we depend on the government-provided data from KESIS and EPSIS.

4. Results

4.1. Key Indicators Identification

Reviewing 27 most recent papers and reports, we identify energy indicators for sustainable development and energy security in Table 1. Using a snowball sampling approach, we start with the broadly known sets of indicators proposed by APERC, IAEA, OECD, and UNWCED, and add new indicators by recent research citing these documents [1,4,7,8,13,33,42]. Some redundant indicators are removed.

The concept of sustainable development encompasses three dimensions of welfare including society, economy and environment [1]. Most energy security indicators also belong to these dimensions. Thus, collected indicators are classified into three dimensions at first, and then into specific themes. It results in the integrated hierarchy of indicators in Table 1. Themes are derived from above-mentioned literature, including four major energy security themes: (1) availability; (2) accessibility; (3) affordability; and (4) acceptability [8,9].

Given these indicators, five experts evaluate their appropriateness to measure the effects of nuclear energy. Existing literature suggests three criteria: (1) data reliability and availability; (2) specific energy relevancy; and (3) comparability [13]. Above all, if reliable data are not available, or cannot be collected at a national level, the indicator is of little use. Data used for an indicator must be reliable and available not only in some specific sector, but in a whole country. In addition, some indicators are too general to measure the effects of a specific energy source. For instance, energy use per unit of GDP is little affected by increasing use of a specific energy source such as nuclear energy. Another thing to consider is that we will compare effects not only of different nuclear energy options, but also of nuclear and different energy sources. In other words, we need indicators to show effects of nuclear energy, and further to compare its effects with other energy sources including coal, oil and others.

Dimension	Theme	Indicator
		Share of households without commercial energy/electricity
Social	Equity	Share of household income spent on fuel and electricity
		Household energy use for income groups and fuel mixes
	Safety	Accident fatalities per energy produced by fuel chain
		Energy use per capita/unit of gross domestic product (GDP)
		Energy intensity (industry/agriculture/service/commercial)
		Energy intensity (household/transport)
	Availability	Resource estimates
	(use/production)	Resource-to-production ratio
		Reserve-to-production ratio
		Share of energy in total primary energy demand
		Share of energy in total primary energy supply
		Diversity index (energy sources)
Economic		Diversity index (geographical regions)
		Non-carbon energy share in energy
	Accessibility	End-use energy price by fuel and by sector
	(diversification/trade)	Net energy import dependency
		Political stability of foreign energy supplier countries
		Energy security index
		Shannon/Jansen index
		Stocks of critical fuels per corresponding fuel consumption
	Affordability (market/price)	Energy price
		Market liquidity
		Bollen's IMP
		Supply-demand index
	Acceptability	Carbon intensity
	receptuonity	Non-carbon energy shares in TPES
		Greenhouse gas (GHG) emissions from energy production and use
	Atmosphere	Concentrations of air pollutants in air
		Air pollutant emissions from energy systems
Environmental	Water	Contaminant discharges in liquid effluents from energy systems
		Rate of acidification of soil area
		Rate of deforestation
	Land	Rate of solid waste generation to units of energy produced
		Rate of solid waste properly disposed of to total solid waste
		Rate of solid radioactive waste to units of energy produced

Table 1. Energy indicators for sustainable development and energy security.

Table 2 shows the evaluation results. For any single indicator, data are available. However, data are difficult to find or not available for some integrated indicators including Shannon index, supply–demand index, and Bollen's IMP. In addition, some qualitative indicator such as political stability has little reliable data. Most descriptive indicators of energy use are little relevant to nuclear energy. Filtering out these indicators, we can narrow down to a set of nuclear energy indicators with guarantees for data availability, nuclear energy relevancy and performance comparability.

The relative importance of different indicators varies by countries because national energy priorities depend on country-specific factors and conditions [13]. In the First National Energy Plan,

Korea announced primary objectives of national energy policies [43,44]. Our five experts match these objectives with relevant nuclear energy indicators, thereby selecting key nuclear energy indicators to measure achievement of Korean major energy policy objectives. When there are similar indicators under same policy objective, five experts are asked to rate the degree of impact of policies on the designated indicators. The five-point Likert scale is used from 1 (very low impact) through 3 (modest impact) to 5 (very high impact). Indicators with larger degree of impact are selected because it can better represent changes in policy-related effects.

Indicator	Nuclear Energy			
multator	Data Availability	Relevancy	Comparability	
Share of households without commercial energy/electricity	0			
Share of household income spent on fuel and electricity	0			
Household energy use for income groups and fuel mixes	\triangle			
Accident fatalities per energy produced by fuel chain	\triangle	0	0	
Energy use per capital/unit of GDP	0			
Energy intensity (industry/agriculture/service/commercial)	0			
Energy intensity (household/transport)	0			
Resource estimates	0	0	0	
Resource-to-production ratio	0		0	
RPR	0	0	0	
Share of energy in total primary energy demand	0			
Share of energy in total primary energy supply	0			
Diversity index (energy sources)	0			
Diversity index (geographical regions)	\bigtriangleup	0	0	
Non-carbon energy share in energy	0	0	0	
End-use energy price by fuel and by sector	0	0	0	
NEID	0	0	0	
Political stability of foreign energy supplier countries	\triangle	0	\triangle	
Energy security index	0	0	0	
Shannon/Jansen index	\triangle	\triangle	\bigtriangleup	
Supply-demand index	\triangle	\triangle	\bigtriangleup	
Stocks of critical fuels per corresponding fuel consumption	\triangle	0	0	
Energy price	\triangle	0	0	
Market liquidity	\triangle			
Bollen's IMP	\triangle			
Carbon intensity	0	0	0	
Non-carbon energy shares in TPES	0	0	0	
Greenhouse gas emissions from energy production and use	0	0	0	
Concentrations of air pollutants in air	0	0	0	
Air pollutant emissions from energy systems	0	0	0	
Contaminant discharges in liquid effluents from energy systems	0	0	0	
Rate of acidification of soil area	0			
Rate of deforestation	0	0	0	
Rate of solid waste generation to units of energy produced	0	0	0	
Rate of solid waste properly disposed of to total solid waste	0	0	0	
Rate of solid radioactive waste to units of energy produced	0	0	0	

Table 2. Appropriateness evaluation of indicators for nuclear energy.

Notes: \bigcirc (the criterion is fully met), \triangle (the criterion is partly met).

Seven key indicators more than average of 4.4 points by experts are identified as shown in Table 3. Nuclear energy is regarded as an energy option to reduce high dependency on imported fossil fuels with advantages of more stable supply and price. Thus, a set of RPR, NEID and energy price can address such policy objectives better than others. However, there are strong concerns about environmental risks including accident fatality and radioactive hazard. Three indicators about accident fatality, solid radioactive waste production, and its disposal are selected to reflect such concerns. Any energy option must consider the objective of the low-carbon economy. Thus, we put non-carbon energy shares in TPES into the environmental dimension. Overall, seven indicators are well-balanced over major dimensions and themes of sustainable development as well as energy security, and also over Korean policy objectives.

Dimension	Theme	Policy Objective	Indicator	
Social	Safety	Energy safety network Accident fatalities per energy prod by fuel chain		
	Availability	Overseas energy development RPR		
Economic	Accessibility	Stable energy supply (Nuclear and renewable energy supply expansion)	NEID	
	Affordability	Efficient energy market (Less energy price volatility)	Energy price	
Environment			Non-carbon energy shares in TPES	
	Acceptability	Climate change adaption	Rate of solid radioactive waste properly disposed of to total solid radioactive waste	
		The Let energy wellings	Rate of solid radioactive waste to units of energy produced	

Table 3. Key nuclear energy indicators in Korea.

4.2. Comparison of SFR with PWR

As previously noted, SFR is regarded as one of favorable nuclear energy options in Korea. Under the Fourth Comprehensive Nuclear Energy Plan by Ministry of Education, Science and Technology, SFR will be designed, and developed by 2020 [45]. The first SFR nuclear plant is expected to be built and to produce electricity around 2050. The overall capacity will gradually increase from 3 GW to 18.4 GW over 2050–2100. SFR nuclear plants will replace old PWR or coal power plants. In order to maximize positive effects of replacement, the government must compare SFR with PWR, and also with coal electricity generation from the perspectives both of sustainable development and energy security.

Considering this, we measure effects of SFR and PWR over five themes. The future scenario of SFR introduction by Ministry of Education, Science and Technology is used as a basis of all assumptions. Some indicators are slightly modified for intuitive comparison. Accident fatality is in nature qualitative, and thus is replaced by the nuclear accident cost. With reference to Rabl and Rabl, we set its key parameters as shown in Table 4 [34].

Category	Parameter	Value	SFR Cost	Parameter	Value	PWR Cost	
Reactor	Cost per GW	\$2.17 B/GW	\$5.2 B	Cost per GW	\$5.5 B/GW	\$13.2 B	
incuctor	Capacity	2.4 GW	ф01 2 В	Capacity	2.4 GW		
Lost power –	Unit cost of electricity	\$0.0494/kWh		Unit cost of electricity	\$0.0542/kWh		
	Annual running hour	7524 h	\$3.5 B	Annual running hour	7524 h	\$3.9 B	
	Discount factor	0.78		Discount factor	0.78		
Cancer	Average cost per cancer	\$5,545,242		Average cost per cancer	\$5,545,242		
	Number of cancers	10,000	\$21.1 B	Number of cancers	10,000	\$21.1 B	
	Discount factor	0.38		Discount factor	0.38		
– Environment – –	Area lost for agriculture	1000 km ²		Area lost for agriculture	1000 km ²		
	Annual yield	500 t/km ²	\$1.6 B	Annual yield	500 t/ km ²	\$1.6 B	
	Average price	\$166.3/t		Average price	\$166.3/t		
	Discount factor	0.38		Discount factor	0.38		

Table 4. Parameters and costs of nuclear accidents.

Notes: TW (terawatt), GW (gigawatt), kWh (kilowatt-hour), \$ B (billion US dollar) and t (ton).

Korean government assumes cost of \$2.6 B for 1.2 GW SFR-based nuclear capacity. Rabl and Rabl assumes \$5.5 B/GW for 6 GW PWR-based nuclear capacity [34]. For comparison, we assume same capacity of 2.4 GW both for SFR and PWR. On the ground that SFR could achieve its cost competitiveness objective, its unit cost of electricity is assumed to be \$0.0494/kWh which is less than \$0.0542/kWh of PWR. Average running rate of all Korean nuclear power plants is 85.9% in 2015, meaning 7524 annual running hours. Using this, we calculate cost of lost annual power. Considering the average reconstruction period, we assume that cost of lost power should occur over next five years. A discount factor of $(1 - 0.05)^5 = 0.77$ is applied to the cost of lost power with assumption of 5% interest rate. Costs of cancers and agricultures are same for SFR and PWR. It is of little use for comparison between nuclear energy options, but will be useful for comparisons with other energy sources. All parameter values including average cost per cancer and area lost for agriculture are based on IAEA and Rabl and Rabl [13,34]. Note that the duration of agricultural loss and cancer treatment is assumed to be 20 years.

As shown in Table 5, oxide and metal-alloy fuels for SFR and PWR include uranium, plutonium, zirconium and others [25]. These core resources such as uranium are commonly estimated to be, at least, more than 100 years [46]. Therefore, there is little difference between RPRs. SFR has advantages of efficient use of fissile materials and multi-recycle. It therefore reduces uranium imports, improving the NEID. Less uranium imports lead to less exposure to the international uranium market, and thus results in reduced ESIprice. Non-carbon energy share in TPES has little difference between SFR and PWR, and therefore is not used. In addition, all solid radioactive wastes are assumed to be properly disposed. SFR can reuse 93.5% of used PWR fuel while producing some high-level radioactive wastes. It will result in reducing solid radioactive wastes per TWh by 88.8%. Nuclear power plants are assumed to generate 7.5 TWh of power for annual 7524 running hours. Disposal cost per TWh is also reduced by 89.6%. Disposal cost of used PWR fuels per kilogram is assumed to be \$382.84, and that of used high-level SFR wastes is \$255.23.

Dimension	Theme	Indicator	SFR	PWR
Social	Safety	Nuclear accident cost	\$8.7 B	\$17.1 B
Economic	Availability	RPR	>100 years	>100 years
	Accessibility	NEID	0.212	0.228
	Affordability	ESIprice	21.86	21.92
Environment	Acceptability _	Rate of solid radioactive waste to units of energy produced	0.28 ton/TWh	2.53 ton/TWh
		Disposal cost of solid radioactive wastes to units of energy produced	\$93,268/TWh	\$969,861/TWh

Table 5. Effects of SFR and PWR for key nuclear energy indicators.

Overall, SFR will have positive effects on social safety and environmental acceptability more than PWR with slight advantages of economic accessibility as well as acceptability. It therefore is a better future nuclear energy option. Gradual replacement of PWR by SFR is an appropriate policy choice both from the perspectives of energy security and sustainable development.

4.3. Comparison with Coal

We slightly change the scenario of Korean energy mix as used in the previous section. In this scenario, the coal power plant will replace 9 GW capacity of the old PWR-based nuclear power plant over 2020–2040. The objective capacity is reduced to 9 GW because the recently built PWRs will not have to be replaced. Coal power plant is assumed to be built within five to seven years. Time horizon as well as capacity for comparison is therefore changed. Accident cost of coal power plants comprises costs of lost plant and power because other environmental and healthcare costs are relatively ignorable.

On the assumption of 4329 annual running hours and \$0.614/kWh, the cost of lost power is \$0.6 B. The estimated cost of a dual unit advanced pulverized coal power plant with carbon capture storage (CCS) is \$11.3 B for 2.4 GW capacity. Note that a new coal power plant is required to have a CCS under environmental regulation in some countries. Higher capital cost of the coal power plant results in higher accident cost than the SFR-based nuclear plant.

In Table 6, global coal reserves will be sufficient to meet 110 years of global production [38]. However, the RPR in the Asia Pacific region is expected to be less than 51 years. There will be no difference over next several decades, but the availability of coals could be critical after more than 50 years in Asia. With more new coal power plants, energy accessibility and affordability will become worse because of less fuel diversity, similar import dependence and increasing import shares from politically unstable Asia and Middle East. Non-carbon energy shares in TPES will be reduced by 2.9%, thereby accelerating the level of carbon dioxide. The average cost of carbon dioxide reduction with carbon capture storage for pulverized coal power plant is \$27/MWh [47]. It is much more than the disposal cost of used SFR fuel wastes. Over five themes, SFR is obviously a better alternative of power generation than the coal electricity generation on the assumption that the nuclear wastes are properly managed.

Dimension	Theme	Indicator	SFR	Coal
Social	Safety	Accident cost	\$8.7 B	\$11.9 B
Economic	Availability	RPR	230	110
	Accessibility	NEID	0.212	0.254
	Affordability	Energy price risk	21.86	25.033
Environment	Acceptability .	Non-carbon energy shares in TPES	16.2%	13.3%
		Cost of emission to units of energy produced	\$93,268/TWh	\$27,000,000/TWh

Table 6. Effects of SFR and coal electricity generation for key nuclear energy indicators.

5. Discussion

Even if we choose the most suitable indicators in the national energy policy context, a small set of indicators cannot completely capture a broad notion of sustainable development and national energy security. Selection of indicators inevitably leads to simplification. It might miss some important dimensions, thereby making firm statements difficult. For instance, the transport modes including ships, rails, and special carriers have significant effects on dimensions of energy safety, affordability and acceptability. High-level radioactive waste incurs higher logistics costs as well as risks than other used nuclear fuels and energy sources. Its cost and risk depends on the level of available transportation infrastructure and safety technology. However, these factors are not captured enough in our indicators.

For comparison of different energy sources, the indicators also have limitations. Coal power plants produce the emissions of carbon dioxides, nitrogen oxides and others which are different from radioactive wastes by nuclear power plants. Although we can compare their costs of accident, logistics and disposal, some might question whether such comparison makes sense. It might not be fair to compare two qualitatively different damages. Despite such drawbacks, governments have to decide their future energy mix as well as share of each energy source. Policymakers are therefore forced to make comparisons between energy options over many dimensions. Capturing key dimensions of energy security and sustainable development in the national energy policy context, the concise set of indicators should be useful for better policy decisions.

Another limitation is difficulty in identifying the better alternative when there are multiple conflicting dimensions and trade-offs. In our empirical analysis, it is easy to identify the best energy option because SFR is better than PWR and coal electricity generation across all indicators. This is

rarely seen in real multi-criteria decisions. For instance, nuclear energy has advantages of cheaper unit price of electricity, but has disadvantages of much more environmental damages and risks than renewable energies. Some will weigh economic factors more than environmental ones, and others vice versa. Further, there are multiple stakeholders with different interests, perspectives and values. In order to deal with such complex problems involving multiple competing criteria as well as multiple stakeholders, we should use appropriate multi-criteria decision-making method including analytical hierarchy process (AHP), ELECTRE, PROMETHEE and VIKOR [48–50]. These methods have been used to address various energy issues of energy production site selection, policy evaluation, comparison of different energy sources and others [51,52].

Last but not least, the development of symbiotic fuel cycles will make comparison more difficult. Symbiotic cycles use different reactors chains, thereby optimizing the burning process [30]. For instance, light water reactors (LWR)-VHTR-GFR symbiotic cycle used spent nuclear fuel from LWRs as fresh fuel for VHTR and GFR [53]. It has several benefits including exploitation of uranium, reduction of final waste mass as well as radiotoxicity and reduction of plutonium stockpiles. Policymakers consider not only six reactors, but also symbiotic cycles as the GEN-IV nuclear energy options. The increasing number of alternatives is a challenge, but even more difficult is the complexity of comparison due to the mixed benefits and risks of different reactors used in symbiotic cycles.

6. Conclusions

Some countries announced plans to increase the share of nuclear power in the national energy mix, and therefore are moving toward the GEN-IV nuclear reactors. However, there is not a consensus. Governments are forced to reduce emissions under pressure of international environmental protocols and domestic environmentalists. Nuclear power is at the center of controversial debates because it has environmental risks of catastrophic accidents and toxic wastes. In other words, energy security drives some countries toward increasing nuclear power capacity, but sustainable development works as constraints on its growth. Policymakers have to compare several GEN-IV reactors with each other, and further those with other energy options including coal, oil, wind and others. Given so many indicators of energy security and sustainability, they have difficulty in selecting appropriate ones for comparison.

Our method enables policymakers as well as researchers to select appropriate indicators in terms of data availability, relevancy to a specific energy source and comparability. However, as noted in previous studies, indicators must be selected and used in the context. Considering this, we propose a way of identifying indicators that can measure performances of major energy policies in Korea. Through two stages, policymakers can build a concise set of indicators to measure effects of a specific nuclear power option such as SFR on energy security and sustainable development, to compare it with another nuclear power option as well as a completely different energy option. We create paths from needs of energy decision-makers to best suitable indicators. Comparisons between energy options become easier, thereby clarifying consequences of different decisions. Another advantage is to focus on policy objectives while considering economic, social and environmental aspects. It is a challenge to mix policy and economic factors because of their conflicts. Our method allows us to select key factors over different dimensions under policy objectives, thereby contributing to this issue.

Our method shows that SFR is better than PWR and coal electricity generation, but cannot say that it is better than any renewable energy. As previously discussed, multi-criteria decision making methods can deal with multiple criteria and their trade-offs. More heterogeneous energy options therefore become comparable. In addition, our method should be validated by using standard tests, and at least, be compared with widely accepted ones. For instance, the behavioral validity test compares the results of an approach with the observed results by using statistical validity indicators such as root mean square percentage error [54]. Similarly, some well-known models evaluate the effects of different energy options on sustainable development and energy security, including OECD aggregated environmental indices, UN Commission on Sustainability and Development approach [42,55]. Comparison with these models is of great help to improve our approach. Our appropriateness evaluation of indicators

depends on a structured brainstorming technique, but can be improved more by using advanced expert judgment methods. In addition, we use mean value for most indicators. For instance, there are several types of coal power plants. Quantity of greenhouse gas as well as emission reduction cost varies by types of plants, emissions, and reduction methods. Some statistical methods with consideration to distribution and range of values can be of great help to take multiple faces of the future into current decision. Last but not least, we focus on domestic policy conditions, but need to consider geopolitical conditions.

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