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The analysis of security cost for different energy sources

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ABSTRACT

Global concerns for the security of energy have steadily been on the increase and are expected to become a major issue over the next few decades. Urgent policy response is thus essential. However, little attempt has been made at defining both energy security and energy metrics. In this study, we provide such metrics and apply them to four major energy sources in the Korean electricity market: coal, oil, liquefied natural gas, and nuclear. In our approach, we measure the cost of energy security in terms of supply disruption and price volatility, and we consider the degree of concentration in energy supply and demand using the *Hirschman–Herfindahl index* (*HHI*). Due to its balanced fuel supply and demand, relatively stable price, and high abundance, we find nuclear energy to be the most competitive energy source in terms of energy security in the Korean electricity market. LNG, on the other hand, was found to have the highest cost in term of energy security due to its high concentration in supply and demand, and its high price volatility. In addition, in terms of cost, we find that economic security dominates supply security, and as such, it is the main factor in the total security cost. Within the confines of concern for global energy security, our study both broadens our understanding of energy security and enables a strategic approach in the portfolio management of energy consumption.

1. Introduction

Since the oil crises of 30 years ago, energy security has again become a major political issue worldwide. The unfortunate lack of a sound energy security policy has sustained the dependence of OECD countries on oil supplied from politically unstable regions, the dependence of which has not been reduced until quite recently [1–4]. In addition, the concerns for energy security is expected to increase with increasing energy demands worldwide for the next few decades in line with emerging economies and rapidly growing developing countries. Only a few attempts have been made to define and measure the security of energy in order to meet impending policy requests [4–7]. This study serves to fill this near-void by suggesting a model which can measure the cost of energy security while considering energy price volatility, regional concentrations of energy supply and demand, and cost-analysis of various energy sources in the Korean electricity market.

Recent attention in energy security stems from a number global challenges. These are increasing concerns for oil and other fossil fuel depletion, localized geopolitical instability, global agreements for environmental issues, and growing emphasis on welfare issues in government policies. In addition, depletion of oil (and other fossil fuels) is a major factor in energy security. Proven oil and gas reserves, at current prices and technology, are expected to last 40 and 60 years, respectively. This makes the issues of supply problems forefront within the next few decades at least [8–10]. In addition, that the supply volatility in proven reserves of oil and gas has a heavy dependence on politically instable regions such as the Persian Gulf is sensitive. Therefore, combined with the regional concentration problem, depletion of oil and other fossil fuels sparks serious global society issues in the security of energy.

Shifting global geopolitics opens new avenues of vulnerability in terms of energy security. Post cold war geopolitical configuration has resulted in the majority of world power residing in a few political entities, namely, the United States of America (US), Russia, the European Union (EU), Japan, and China. As economic power overshadows military might on the world stage, susceptibility in energy security is now essential in the maintaining of global economic leadership. Therefore, large countries including the US, Russia, and China have invested substantially in military development in order to protect sensitive energy issues. Energy related international conflicts have prompted fear of a geopolitical cold war scenario with energy security being center stage [11].

Increasing concerns for environmental issues, such as the green house gas (GHG) problem and urban pollution further drive our attention towards energy security [4,12]. As Kyoto protocol being effective, GHG concerns have been increased arousing global society to seek alternative energy source which can reduce carbon related pollution. Consequently, nuclear energy has become one of

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the most promising alternative energy sources and directly challenges fossil fuels dominance specifically due to its carbon-free characteristics and efficient cost. However, it (nuclear energy) does have its drawbacks in terms of its environmental "contributions", and as such, it has so far not managed to gain global consensus as the alternative energy source. Indeed, its radioactive waste byproducts are a major global concern. The International Energy Agency (IEA) estimates that China will spend more than 200 billion $ by 2030 on the harnessing of nuclear fuel destined for commercial energy output [13]. Furthermore, India expects to have 25% of its energy provided by nuclear power, a 22% increase of the current statistic [14].

Contrary to these increasing energy security concerns, few attempts have been made to define and measure the cost of the same regardless of impending policy requests. Recently, in the analysis of the increasing dependency of European nations on external energy sources, Costantini et al. [15] suggested dependence and vulnerability indicators based on scenarios using degree of supply concentration and diversity indices regarding oil and natural gas. Grubb et al. [12] also considered diversity of fuel source mix in order to represent a security dimension, and robustness against interruptions of any one source. They applied two different diversity indices to the range of electricity system scenarios when they studied the relationship between low-carbon objectives and the strategic security of electricity in the UK electricity system. These studies considered energy supply irrespective of economic aspects encompassed for example in price volatility and other related impacts. Other studies, Turton and Barreto [4], Correlje and Linde [10], and Mane-Estrada [16] follow these limitations investigating energy security in terms of supply security.

Therefore, in this study, we measure energy security costs for different energy sources contained within the Korean electricity market by considering both supply and economic issues. In measuring the economic security of energy, we consider the degree of supply and demand concentration using the *Hirschman–Herfindahl* index as well as the price volatility of energy sources. We apply our metrics to four energy sources in the Korean electricity market, namely coal, oil, LNG, and nuclear. Through these measures of energy security, we aim to assist in energy security policies.

2. Energy policy in Korea

Korea has experienced tremendous economic growth over the last four decades. In 1955, gross domestic product (GDP) per capita of Korea was only $55; it is over $20,000 in 2007. With this rapid economic growth, Korea tries to achieve sustainable development through an energy policy known as the "3Es" – energy security, energy efficiency, and environmental protection. This is a policy shift, as previously policy focused on ensuring a stable energy supply in order to sustain economic growth and to maintain high-quality lives. As a consequence, Korea's energy policies currently promote a stable energy supply, market efficiency through competition, and implementation of an environmentally friendly energy system with the end-goal of sustainable development.

The tremendous growth Korea has seen in recent decades required a tremendous amount of energy. The lack of limited reserves of indigenous natural resources forced Korea to rely heavily on foreign imports.[1] Currently, the total primary energy supply (TPES) is dominated by oil and coal, though the portion of nuclear and LNG have increased rapidly over the past few years. The TPES increased over nine fold between 1971 and 2004, growing at an average annual rate of 7.3% since 1985 and 4.1% since 1995. In the case of LNG, the average annual increase over the last decade has been growing at a rate of nearly 13%, the highest increase among energy sources.

In the case of nuclear energy, Korea was the sixth-largest consumer of nuclear power. The share of nuclear power in its overall TPES was among the 15 IEA countries in 2005. Consumption of natural gas in the industrial sector has also grown 11-folds in the last decade, which is equal to an average annual increase of 27% [17]. In the case of oil, Korea is heavily dependent on imported oil mainly coming from non-OECD countries. Oil accounts for a 57% share of total industrial consumption of energy in 2004. As part of its overall strategy to improve energy security through international project development, the government is securing over 700 million barrels of overseas oil reserves. This is equivalent to the domestic consumption of one year in Korea.[2]

In addition to oil imports, Korea also depends entirely on LNG imports. The bulk of which comes from four countries, namely Indonesia, Malaysia, Oman, and Qatar, which supplied over 90% of total LNG imports in 2004. Complementing its overseas oil development projects, Korea is securing over 90 million tons (Mt) of gas, or 120 billion cubic meters (bcm), equivalent to approximately four years of annual LNG imports. The government is also working to improve the security of natural gas through additional storage capacity.[3] In the case of coal consumption, over 90% of it is supplied in the form of imported bituminous coal primarily from Australia, China, and Indonesia. Domestic resources are almost exclusively anthracite coal, a low quality coal. To enhance security of supply and regional economic stability, the government maintains subsidized production and consumption of domestic anthracite coal.

Historically, strategic introduction of nuclear energy in 1958 played an important role in the rapid economic growth of Korea. In 1945, the total capacity of electric power generation was only 1.7 GW and the actual amount of electric power generation was just 0.1 GW. In addition, most of the power plants were placed in the northern part of Korea prior the Korean war in 1950. After the Korean war, sufficient energy supply was an urgent problem for the whole nation. Under this situation, the government strategically introduced nuclear energy in order to increase domestic electricity generation facilities and to implement a nuclear power program for the future. At that time, worldwide opinion on the use of nuclear power plants was divided. In 1958, the Korea–US atomic energy agreement for peaceful use of nuclear energy was thus contracted. To this day, nuclear power is a major energy source in Korea.

Fig. 1 shows the history of electric power generation by via various energy sources. Energy policy changes leave a clear mark in that figure. Pre-nuclear, oil was the major source of (electrical) energy providing up to 80% of the total. However, after nuclear power plants were turned on, electricity production using oil sharply decreased. Since, the Korean government introduced nuclear energy, the dependency on the same has been also continuously increasing and the domestic electricity supply has remained stable even through oil price fluctuations.

Currently, the total installed capacity of electricity generation in Korea is 60 GW, this is 20 times larger than that of 1975. The government expects electricity demand to grow steadily at a 4% rate to 5% per year [18]. As part of this plan, nine nuclear power plants are scheduled to be built between 2005 and 2017. Over the last decade, growth of nuclear power plants is still high compared to other

[1] Korea has no oil reserves and has small amount of LNG which has been produced since 2005 as along with some low-quality coal reserves.

[2] Since joining the IEA in 2002, Korea's oil stocks have never fallen below the IEA's 90-day net import requirement.

[3] It plans to increase its total storage capacity rate from 8.8% of annual consumption to 12.7% by 2017.

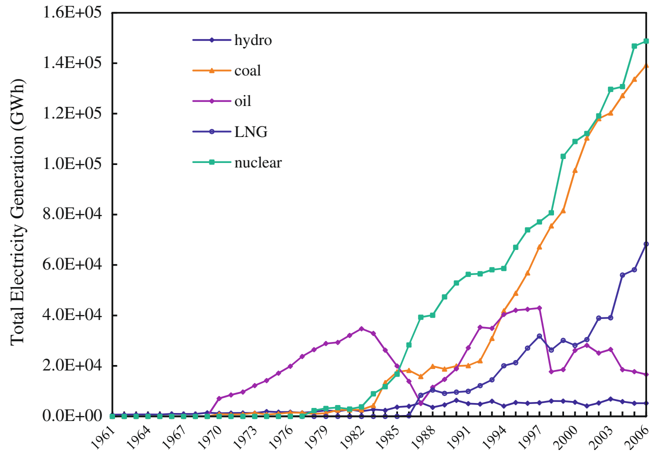

Fig. 1. History of the electric power generation by energy sources in Korea.

IEA countries; however it has subsided somewhat compared to the past. As the standard of living becomes higher in Korea, the demand for electricity also becomes higher. Therefore, Korea faces the need for urgent strategic approaches in policy in order to secure highly reliable energy resources for the future electricity generation under a changing economic environment and its economic structure. This is an important national issue.

3. Cost of energy security

3.1. Definition of energy security

Energy security can be defined as a reliable and uninterrupted supply of energy sufficient to meet the needs of the economy at the same time, coming at a reasonable price [19].[4] Based on that definition, the European Commission (EC) suggested four dimensions of energy security: physical, economic, social, and environmental. A physical disruption refers the case when an energy source is exhausted or production is stopped either temporarily or permanently [15]. The concerns for the depletion of oil and other fossil fuels are relevant when there is a high probability of physical disruption. Therefore, energy security form the point of view of physical disruption contains classic concepts such as ensuring stable energy supply capability based on the balanced distribution of supply sources in order to reduce the risk of supply disruption.

Economic disruptions can be defined as the case when the market price of energy fluctuates and consequently disturbs and damages regular economic activities and systems. Therefore, in economic disruptions, volatility of energy prices, and the corresponding cost fluctuation are the main source terms in energy security. Social disruption is chiefly related to geopolitical instability. Instabilities of such a type in global regions that are major supplies of energy resources are often magnified by conflict amongst countries with different political, ideological, and religious backgrounds. Lastly, environmental concerns are related to polluting emissions such as greenhouse gas and urban pollution [15]. Here we can further classify the dimensions of energy security into direct and indirect factors. Direct factors include *physical and economic disruption*. Indirect factors are associated with *social and environmental disruptions* that indirectly influence energy security.

Based on the above definition and categorization, we can narrowly define energy security only within the context of the direct factors, that is, physical and economical disruption, and we can broadly define the same within the context of the indirect factors, namely, social disruption. Because the direct factors incorporate the effect of indirect factors inherently, it is more reasonable and reliable to quantify and measure energy security under the narrow rather than the broader definition. However, climate change mitigation effect is crucial in energy security, future scenario for future fuel cost were made. In this work, we therefore adopt the narrow definition in order to derive the cost of energy security and its index for four major sources of energy – oil, coal, LNG, and nuclear energy.

3.2. Climate change mitigation effect

Climate change is a crucial issue in worldwide. However, no form of energy production or use is without environmental impact. This is true for all energy chains: from extracting resources, building facilities, and transporting material through the final conversion to useful energy services. Thus, we should have to consider the effect of the climate change in the energy security cost. However, no clear actions are taken, we should have to make a scenario for the future.

This scenario differs from the reference only in that the Korean power sector is subject to a tax of $25 per ton of CO_2 emitted. And the other environmental pollutant such as SO_2, NO_2, and TSP (total suspended particle) are also considered. The scenario used a constant real discount rate and no escalation, in real terms, in the fuel prices. For purposes of simplicity, the scenarios initially assume that these prices remain the same in constant monetary value over the study period. This assumption implies that the future price increase will be in line with the overall inflation rate in the country. However, to illustrate the impact of relative changes of the energy security due to the climate change and hence on the relative competitiveness of different generating options, a set of higher international fuel prices was applied.

The levelized generation cost of current new nuclear technologies is about 8% cheaper than for coal. With increasing plant-size, the levelized generation costs of both nuclear and coal are expected to decline but their relative difference is expected to remain about the same. The size of the LNG plant is expected to increase, but without any significant effect on investment costs. Despite the lowest specific investment cost and the highest conversion efficiency, the high costs of imported LNG mean the levelized generation cost from LNG plants will remain much higher than that of nuclear and coal.

3.3. Cost of supply security

Based on the above definition, we first measure the supply cost of energy security for different energy sources. Here we limit our measurement of the security cost to the case of *physical disruption in electricity generation* in order to consider only the case where we can clearly quantify the result with concrete and reliable data. Therefore, the cost of supply security here means the opportunity cost a country or a geopolitical region pays in electricity generation under the possibility of an energy source supply disruption during a specific period. As mentioned above, physical disruption of an energy supply is defined as the exhaustion or cessation of production of energy. Whatever the reason, supply disruption of an energy source causes damage and incurs cost to the economic system of a country in terms of GDP loss. That this is the case is true as the (economic) system takes time to adjust itself to a different configuration of energy consumption after the disruption. Since, reserves or stocks of the energy in that same country will reduce the cost from the supply disruption, we also consider these reserves in measuring the cost of supply security.

[4] In the case of OECD/IEA, energy security has been defined as the availability of a regular supply of energy at an affordable price [20].

Consequently, two factors are critical in measuring the cost of supply security; one is the possibility of sudden disruption in fuel supply, and the other is the availability of energy stocks and reserves in a given country. Therefore, we measure the security cost of energy supply through amount GDP losses equal to the GDP contribution of a specific energy source in terms of electricity generation and excluding the amount of contribution from the reserve of the energy. Surely, it will be close to the *minimum cost* a country will pay under supply disruption when we count other costs such as welfare loss, adjustment cost for new energy consumption system, additive environmental cost, etc. Therefore, we emphasize the point that the cost we suggest here is *the minimum cost* a country pays from supply disruption confining the case to *electricity generation*. Regarding the periods of supply disruption, we consider three cases, 6 months, one year, and two years, while we attain the consistency with the case of economic disruption discussed later in this work. Therefore, the cost of supply security (C_{Si}) can be defined as follows:

$$C_{Si} = \pi_i \cdot (G_i - R_i) \tag{1}$$

where G_i is the total amount of GDP incurred by the electricity generation with the supply of an energy *i*.[5] R_i represents the amount of GDP which can be generated from the reserve of an energy *i* when the supply of energy *i* is disrupted in terms of electricity generation. The longer an energy source can support an economy under its supply disruption with more reserves, the lower the cost of supply security is for the country. π_i is the energy '*i*' supply disruption probability which takes into account supply disruptions stemming from both depletion and geopolitical instability as indicated in Table 1. In case of the disruption probability from depletion, we consider the inverse of the periods an energy source can last under the current economic system. Regarding the disruption probability from geopolitical instability, we use the global peace index (GPI) which measure 121 countries' geopolitical stability and peacefulness based on a 24 different indicators.

In case of oil, there has, in the past been several supply disruptions of interest [21]. We can categorize the causes thereof into four categories: political reasons including domestic (economic) problems in OPEC countries, acts of terror and/or sabotage directed towards oil facilities, wars in the OPEC countries, and disruptions in the ocean transportation network. In political category[6], we consider the domestic problem and wars which are closely related to the supplier countries' stability. In the case of terror or sabotage and transportation network disruptions, we do not consider political factors in our measurement because their data is limited and quantification is difficult. Therefore, one should note that our measurement of disruption probability might be under estimated.

3.4. Cost of economic security

Although there have been a few attempts to try to measure the security of (energy) supply using a diversity index, such as the *Shannon–Weiner index*, the effect of price shocks on economic system has not been considered in analyzing energy security. Grubb et al. [12] measured security of energy supply using a diversity index following the concept suggested by Stirling [21]. They used *Shannon–Weiner* and *Herfindahl–Hirschman* indices concentrating on diversity in technologies as grouped by fuel sources for a range of future scenarios each of which describes the fuel mix in a future electricity system in UK. Costantini et al. [15] also used a *Shannon–Weiner* index in order to analyze dependence and vulnerability of the European energy system through a comparison of energy scenarios produced by International Energy Agency (IEA). Although, a number of other studies have tried to develop economic measures [22–24], they did not take into account price volatility in suggesting economic measures of energy security. Therefore, we suggest the cost of economic security (C_{Ei}) as follows:

$$C_{Ei} = \omega_i \cdot \varphi_{pi} \cdot v_{pi} \cdot c_i = H_i^* \cdot \varphi_{pi} \cdot \sqrt{\frac{1}{\tau(n-1)} \sum_{t=1}^{\tau} (v_t - \overline{v})^2} \tag{2}$$

where $v_t = p_t - p_{t-1}$

$$H_i^* = \frac{(H_i - \frac{1}{n})}{(1 - \frac{1}{n})}$$

where ω_i is the degree of supply and demand concentration for energy source *i* regarding supply and demand in the country, φ_{pi} is the portion of the fuel price which is used to generate electricity for each energy source *i*, v_{pi} is the volatility of a price for energy source *i* in the country, and c_i is the unit cost to generate electricity from each energy source. [25]. Here, we use the *normalized Hirschman–Herfindahl index* (H^*_i) for the degree of supply and demand concentration (ω_i) where H_i represents the *Hirschman–Herfindahl index* for supply and demand for energy *i*, and *n* is the number of energy sources in the country. In the case of price volatility, we use the standard deviation of price differences over specific periods where the observed price for interval *t* is p_t, $\overline{v}$ is the mean value of v_τ, and *T* is the length of the interval in years [25]. Therefore, C_{Ei} is the opportunity cost a country pays for the security of energy source *i* when the price fluctuates more frequently compared to the average price of the energy in order to generate one unit of electricity (1 kW h).

In Eq. (2), the standard deviation of price differences is commonly used as a measure of price volatility [26–30]. We can also take logarithms of the prices in defining v_τ based on a *Wiener process* which is used to describe random walks and Brownian motion. However, the definition in logarithmic form fails in situations where zero or negative prices are expected [25,31]. Therefore, we take ordinary Wiener process with a normal distribution of price differences.

The *Hirschman–Herfindahl index* (*H*)[7] has been used as an indicator of the degree of competition in an industry using the market share of firms and widely applied in the analysis of competition for antitrust law and industry regulation. In this paper, we use the market share of an energy source *i* instead of a firm's. *H* is clearly coupled with two dimensions, those being the number of energy sources and the inequality of their market shares. *H* thereby provides an easily interpretable measure of concentration. For a given number of energy sources, *H* increases as the dispersion of their market shares increases.

Among the several types of *Hirfindahl indices*, we chose the normalized (value ranges from 0 to 1) *Hirschman–Herfindahl index* (H^*) in our measurement. If the number of energy sources is held con-

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[5] The contribution of electricity generation to GDP is fixed regardless of energy sources.

[6] In case of nuclear energy, current situation regarding nuclear proliferation is maintained in the future in political perspectives.

[7] The Hirschman-Herfindahl index (*HHI*) is defined as the sum of squares of market shares of firms (in some market). It provides an easily interpretable measure of concentration, where S_j is the percentage of market share of a firm *j* and *n* is the number of firms in the industry:

$$HHI_i = \frac{1}{n} + nV$$

where

$$V = \frac{1}{n} \sum_{j=0}^{n} \left(S_j - \frac{1}{n}\right)$$

V above is the statistical variance of the market shares. For a given number of firms, *HHI* increases with the dispersion of firms' market shares (skewness) increases.

Table 1
Cost of supply security (C_{Si}) in electricity generation of Korea.

	Disruption probability (π)	GDP loss from supply disruption (billion $)	GDP gain from reserve (billion $)	Net GDP loss from supply disruption (billion $)	Cost of supply security (C_{Si}) (cents/kW h)
Oil	2.100×10^{-3}	29.119	7.977	21.141	0.318
Coal	7.120×10^{-4}	263.686	21.673	242.013	0.136
LNG	9.579×10^{-4}	127.246	5.229	122.017	0.192
Nuclear	1.372×10^{-3}	284.105	284.105	0.000	0.000

stant, then a higher variance due to a higher level of asymmetry among energy sources in supply or demand will result in a higher value of concentration [32,33]. The invariance of its range is a property of H^* that allows it to be used to measure diversification as well as concentration by simply inverting it [32,36–38].[8]

In order to measure the C_{Ei}, not only the concentration of supply, but also that of demand is important in the fluctuation of price. If the market structure shifts towards a monopoly, from large to small number of consumers, i.e. as the degree of demand concentration increases, the market power decreases for suppliers. In other words, the degree of supply or demand concentration both affects the price setting mechanism and its stability in the market. Therefore, price fluctuation probability increases when the degree of concentration becomes higher for both supply and demand. To capture this phenomenon in the calculation of economic security, the H^* index for both supply and demand are considered.[9] Therefore, if the supply or demand is concentrated in sources or regions, C_{Ei} will have a high value reflecting the situation where we have a large possibility of having volatile prices due to the monopolistic supply or demand configuration of the market.

Consequently, C_{Ei} evaluates the opportunity cost of price shock (volatility) which a country pays in order to maintain its economic system without disturbing the supply and demand configuration of its market.[10] If the concentration of fuel supply and/or demand becomes high with respect to a fuel source, the economic cost of energy security increases by imposing more weight to the price volatility than when the concentration is low and vice versa. In addition, if the portion of the fuel cost is high, the shock will be also high. Therefore, the measure indicates that more concentrated the fuel resources, the higher the probability of having price fluctuations, and consequently, we have high value of C_{Ei}.

4. Results and discussion

We examine the case of electricity generation in Korea as means to provide data for empirical analysis. Regarding the amount of electricity generation that Korea generated in 2006, or 345, 260 GW h annually, which equates to 1/12 of the United States and 1/3 of Japan, the portions of the different energy sources are 39.4%, 36.6%, 17.6%, 4.0%, and 1.4% for nuclear, coal, LNG, oil, and hydro, respectively [39]. Interestingly, nuclear and coal take about 80% of total energy supply even though coal needs a large space for reservation. In the case of nuclear, it (the fuel) lasts at least one year without any need for additional reservation once it is installed in the nuclear power plant (as is the case for other reactors worldwide). Consequently, different energy sources give us different security costs for the electricity generation due to the inherent characteristics regarding reserve and their different portions of electricity generation.

4.1. Cost of supply security

In Table 2, we show the probability of supply disruption (π_i), GDP loss from supply disruption, GDP gain from energy reserve, net GDP loss from supply disruption, and the cost of supply security (C_{Si}) for the four major energy sources in Korea considered in this work. One should note that the estimated values in the last column are *opportunity costs* of Korea in view of energy security in supply. In other words, Korea can reduce these costs by balancing the distribution of supply sources or selecting a supplying country based upon geopolitical stability. In addition, the values in the column are the *minimum costs* that one can consider since we do not include sequential losses from the disruption of electricity generation such as welfare loss, damages of production system, and cost of recovery, etc.

As indicated in the last column of Table 1, cost of supply security is highest for oil (0.318 cents/kW h), followed by LNG (0.192 cents/kW h), coal (0.136 cents/kW h), and nuclear (0.000 cents/kW h). The GDP losses from disruption are proportional to its contribution to electricity generation. Therefore in the case of oil, although its net GDP loss is low (21.141 billion $) due to its contribution for the electricity generation is only 4% of the total electricity generation. However, oil has the highest security cost per unit electric power because of both highest probability of fuel disruption (2.100×10^{-3}) and the difficulty of securing stock. Maximum probability of disruption results from its limited

Table 2
Geopolitical instability index.

Country	Geopolitical instability	Country	Geopolitical instability
Iraq	3.437	Brazil	2.173
Russia	2.903	Ukraine	2.150
Nigeria	2.898	Kazakhstan	1.995
Uzbekistan	2.542	China	1.980
India	2.530	Libya	1.967
Algeria	2.503	Kuwait	1.818
Venezuela	2.453	UAE	1.747
South Africa	2.399	Qatar	1.702
Iran	2.320	Australia	1.664
United States	2.317	Germany	1.523
Saudi Arabia	2.246	Canada	1.481

Note: above values are derived based on the GPI (source: [41]).

[8] Although there has been other diversity indices, such as *the Hall–Tideman–Rosenbluth Index* [32] and *Kwoka function* widely used in ecological studies, such as *the Hall–Tideman–Rosenbluth Index* (Halland practice to *the Hirschman–Herfindahl index* (H) and *the entropy measure* (E or *Shannon–Weiner index* in ecology literatures), we use H rather than *the entropy measure* as the weight for the price volatility. E is a direct measure of diversification and cannot be inverted as readily as H to yield a measure of concentration because its normalized range varies corresponding to the value of n, even for large values of n [32]. In addition, E can in theory take on very large and thus noncomparable values as its upper limit [34,35]. Although, Stirling [21] argued that E is more desirable than HHI because the changes of exponent in H lead to radically different rank orderings for different system, since it incorporates the concept of *variety* and *balance*, Acar and Sankaran [31] pointed out that HHI and E are not directly comparable and H also has the property of *variety* and *balance* as E. US the Department of Justice considers a market with H greater than 0.18 to be a concentrated market. We normalized H with 0.18 following their approach.

[9] We also normalized H^* across energy sources as the highest H^* to be one when we apply H^* into C_{Ei} derivation in order to secure consistent measure across energy sources.

[10] Hamilton [40] showed in a general equilibrium model that fluctuations in the supply of primary commodities can increase unemployment and decrease aggregate output. Based on his model, importer economies are more vulnerable to fluctuations in oil prices than to similar volatility in other commodity prices. This explains how volatility of energy price important in the economic system of a country.

supply and the fact that much of it comes from geopolitically unstable countries.

In the case of nuclear, although its net GDP loss highest (284.105 billion $) among the energy sources, its cost of supply security is lowest because of its low probability of disruption (1.372×10^{-3}). This value can be further reduced by application of fuel reprocessing and recycling technologies. Its fuel is also relatively easy to stock compared to the other fuel sources. Therefore, nuclear energy has almost no cost of supply security due to its distinctive characteristics as a high density energy source, sustainability, and small physical size. GDP loss of coal is quite large due to its large contribution to electricity generation. Conversely, its C_{Si} is low compared to nuclear because of its low disruption probability (7.120×10^{-4}). The latter stems from abundance compared to the other resources. In Table 2, we show the geopolitical instability of countries which supply the four major energy sources used in Korea. Clearly, Iraq is the most unstable, and Norway is the least unstable.

We also analyze the cost of supply security (C_{Si}) for different time periods of supply disruption as shown in Fig. 2. Contrary to the low increase of their supply security cost for LNG and coal, oil shows a rapid increase in its cost of supply security as the disruption period grows. This is due to its high probability of disruption and low capacity for reserve. In the case of nuclear energy, the cost of supply security is near zero. However, the cost increases rapidly after one year due to the limited amount of uranium reserves in Korea.[11] The rankings of supply security cost remain steady with respect to the extension of disruption periods. This results in a high cost for oil and a low cost for nuclear.

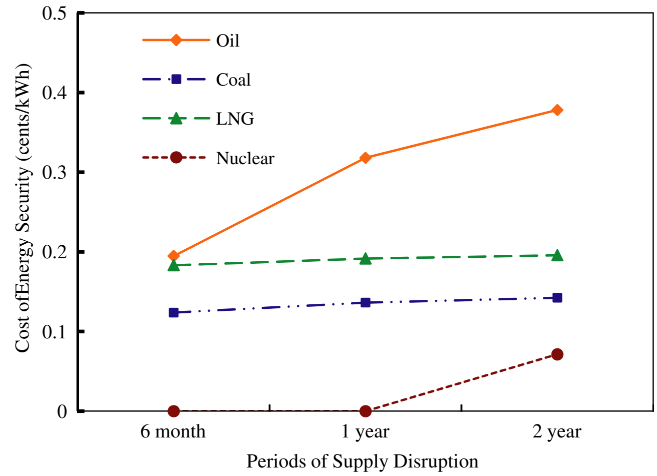

Fig. 2. Supply security cost (C_{Si}) for various disruption periods.

Table 3
Economic security cost (C_{Ei}) and related factors in electricity generation of Korea.

	Price volatility (υ_{pi})	Portion of fuel cost (φ_{pi})	H_i^*	Cost of economic security (C_{Ei}) (cents/kW h)
Oil	0.155	0.730	0.276	0.385
Coal	0.120	0.470	0.556	0.134
LNG	0.278	0.780	0.391	1.347
Nuclear	0.107	0.110	0.377	0.018

4.2. Cost of economic security

Table 3 shows the cost of economic security, C_{Ei} and factors affecting its values – price volatility of different energy sources, *Hirschmann–Hirfindahl* indices of supply and demand, and the portion of the fuel price used to generate electricity for each energy source *i* in Korea. As indicated in the figures, the cost of economic security is highest for LNG (1.347 cents/kW h) followed by oil (0.385 cents/kW h), coal (0.134 cents/kW h), and nuclear (0.018 cents/kW h). LNG has highest price volatility (0.278) and the highest portion of fuel price to electricity generation (0.780). This reflects the situation of LNG being the most unstable energy sources among the four energy sources within the perspective of economic security. Following LNG, oil has the second largest values of economic security as expected from the considerations of both the second highest price volatility value (0.155) and its portion of fuel cost (0.730). Nuclear energy has the lowest price volatility (0.107) confirming that it is the most stable energy source in Korea in terms of economic security.

Here, we find that price volatility of LNG (0.278) is almost 2.5 times higher than that of nuclear energy (0.107). This reflects the situation where the market for LNG is highly unstable compared to nuclear energy sources. In the case of *normalized Hirschmann–Hirfindahl* index, H^*, LNG shows the highest supply concentration due to geopolitical location, namely Russia and Iran. In the case of coal, we find that the highest concentration in demand is due to China's recent economic growth. Although nuclear has the high H^* value, its C_E is lowest (0.018 cents/kW h) because price volatility (0.107) and the portion of its price in electricity generation (0.110) are small compared to the other energy sources. One should note that coal is also a competitive resource in terms of economic security perspective (0.134 cents/kW h).

4.3. Security cost of energy

In Table 4, we show total costs of energy security integrating the cost of supply and economic security for different energy sources under different supply disruption periods. The most secure energy source is nuclear energy, followed by coal, oil, and LNG, as you can find its value of 0.018 cents/kW h for 6 months and one year, and 0.089 cents/kW h for two years. In contrast, LNG shows the highest security cost (1.530 cents/kW h for 6 months and 1.538 cents/kW h for one year) due to its large economic cost of security (1.347 cents/kW h). The latter stems from its high price volatility and fuel price portion. Although oil has the highest cost of supply security (0.318 cents/kW h as shown in Table 1), the cost of economic security for LNG (1.347 cents/kW h as shown in Table 3) is much higher and it compensates C_{Si} of oil resulting in the highest total security cost for LNG.

As seen in Tables 1 and 2, the cost of economic security (C_{Ei}) is relative larger than that of supply security (C_{Si}) resulting in the situation where the cost of economic security dominates total security cost (of an energy source). Consequently, due to sudden fluctuations of LNG prices in the past few years, its total security cost (*Ci*) is highest amongst the four energy sources in Korea, and nuclear shows the lowest cost due to its low price volatility in the market. Here we should note again that this cost of energy security is an *opportunity cost* for using the energy source considering the various security environments. One can reduce this cost by diversifying the supply sources, having long term contracts with fixed prices, etc. Based on these results, it is reasonable for Korea to depend more on nuclear energy and coal than on LNG and oil for its energy strategy when consideration of the different security costs of different energy sources is taken into account.

[11] Nuclear energy can last 60 times longer periods of time once uranium is reprocessed and if Pu is used as a new source, it also can last 60 times more than current periods of time.

Table 4
Energy security cost (C_i) for various disruption periods in electricity generation of Korea.

	6 Months			1 Year			2 Year		
	C_i (cents/kW h)	C_i^* (cents/kW h)	Total cost (million $)	C_i (cents/kW h)	C_i^* (cents/kW h)	Total cost (million $)	C_i (cents/kW h)	C_i^* (cents/kW h)	Total cost (million $)
Oil	0.579	0.875	40.444	0.703	0.999	98.111	0.763	1.059	212.978
Coal	0.258	0.486	162.843	0.270	2.551	341.546	0.276	0.504	698.523
LNG	1.530	1.665	466.709	1.538	1.674	938.566	1.543	1.678	1882.142
Nuclear	0.018	0.018	12.176	0.018	0.020	24.352	0.089	0.089	243.096

C_i^* represents security cost of each energy source including the climate change mitigation effect.

5. Conclusions

Global concerns for the security of energy have increased in recent years due to increased geopolitical instability and changing international perception of energy sources as a strategic intermediary for economic growth. Surprisingly, few attempts have been made to define energy security and to suggest a quantitative measure and means of comparison. Therefore, in this study, we suggest an approach to quantitatively measure and compare the cost of energy security for different energy sources used for electricity generation. Also the effect of the climate change mitigation is considered. In our approach, we take a narrow definition of energy security and measure the cost in terms of supply and economic security. In our measurement of economic security, we consider the degree of concentration in energy supply and demand using the *Hirschman–Herfindahl index* in order to reflect the factors affecting stable prices in the energy market. As an empirical example, we apply our approach to electricity generation in Korea and compare the cost of energy security of four major energy sources, namely, nuclear, oil, coal, and LNG.

We find that, in Korea, nuclear energy is the most competitive energy source in terms of energy security as it has the lowest cost of energy security. Moreover considering climate mitigation effect, the security cost difference between nuclear and other energy sources is increased. Nuclear driven electricity production is then followed by coal, oil, and LNG. Due to its high price volatility and large portion of the fuel price in electricity generation, we find that LNG has the highest cost of energy security among the four sources studied in this work. In case of coal, we find it to be a competitive energy source in terms of economic security due to its stable market price; however, it does have disadvantages in terms of capacity of reserve. Nuclear energy is shown to be the most secure energy sources because of its low price volatility and long sustainability in conjunction with its small physical amount. Its security cost is much lower than any other energy sources in Korea, although, uranium prices have been on the increase in recent years.

In our study, energy security cost can be accepted as an opportunity cost of a country paying for an energy source due to insecurities such as price volatility and supply disruptions. Therefore, a country can reduce its security cost of energy (in terms of electricity generation) by changing its energy consumption portfolio based on the analysis in this work. In other words, our study helps to understand the issues of energy security more strategically and enables one to develop strategic management of energy portfolios for countries under the global concern of energy security. With further extensions of this approach, we will be able to measure the security cost of energy in a global perspective. This is an important issue for today.

One should note that we do not consider the sequential impacts and damages from supply disruption of an energy source in electricity generation when we measure the cost. Therefore, the values we suggest in our study are near minimum values. In future, research along these lines should take into account a broader definition of energy security and encompass broader impacts of supply disruption covering welfare loss, damages of industry system, and recovering cost, and environmental costs, etc., when we measure the cost of energy security. In addition, we also need to consider technological innovation in various energy sectors which will extend the duration of energy consumption periods and increase the efficiency of energy consumption.

Although this paper has some limitations in the measurement of energy security, we believe it has its value as one of the first quantitative studies measuring the cost of energy security and thus broadening our understanding of the issues involved and enabling a strategic management of energy security.

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