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著者(和文)	飯村亜紀子
Author(English)	Akiko Iimura
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Scientific evaluation of Energy Policies; electricity mix decision-making in Japan and international electricity prices in developed countries

Akiko Iimura

Doctoral Dissertation

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Department of Mechanical Science and Engineering
Graduate School of Science and Engineering

Disclaimer

The opinions expressed in this thesis are the author's own and do not reflect the view of the Japanese government and/or any other organization.

Abstract

Energy policy is one of the most important policy areas facing national governments. Achieving energy policy goals requires balancing the different and often competing policies related to environmental protection, energy security, development of national economy and public safety, and on the other hand reaching agreement among various stakeholders whose interests sometimes conflict sharply with each other. It is essential that scientific approaches be applied to organize, analyze and propose rational solutions to controversial, mixed energy policy issues.

In this thesis, the first chapter gives a general overview of world energy outlook and current energy policy issues. Continuous growth of world energy demand, transition to reduced CO_2 emissions, growing introduction of renewable energy, and electrification are key trends. Energy policy on electricity requires greater attention and research on reaching decisions based upon scientific data. Subsequently, two important, interrelated energy policy areas of electricity generation mix and electricity prices were examined in detail in the second and third chapters are introduced below.

Chapter 2: Influence of Safety Risk Perception on Post-Fukushima Generation Mix and its Policy Implications in Japan. Four years after the Fukushima nuclear power plant accident in 2011, an electrical power generation mix policy was finalized and officially approved by the Japanese Government in 2015. During the nationwide discussion process on the proposed policy, opposition by the Japanese public to accept the need for nuclear power was strong. In response, the government correspondently strengthened the nuclear regulatory system and safety standards.

The discussion on the post Fukushima Japanese energy policy was reviewed to assess the historical role of nuclear energy in achieving the

traditional 3Es policy goals i.e., economic growth, energy security, and environmental protection, and how this policy has been challenged by general public opinion after the accident. A three-layer Analytical Hierarchy Process (AHP) model with the 3Es and two opposing views on safety as independent criteria in the criteria layer was introduced in order to compare and analyze these competing energy policies in the second section. Results in the third section show that the highest nuclear power proportion scenario of 20% nuclear in the generation mix among three electricity mix scenarios proposed by the Japanese Government in 2012 is the most appropriate when safety is measured with human fatalities as a scientific measurement of risk. Although this may appear contradictory to the public preference of eliminating nuclear energy in Japan altogether, the statistically low human fatalities, when scaled to electrical power generated, indicates that it is the safest electricity generation mix. This study clearly revealed that opposing viewpoints on safety result in choosing different electricity generation mixes and showed the effectiveness of scientific approach to policy decision-making.

Chapter 3: Renewable energy's impact on international household electricity price in liberalized electricity markets - panel data analysis on selected developed countries. Electricity market reform has also been a major energy policy agenda item since the late 1980's in many developed countries aiming to create a more competitive market environment. In the 1990's, climate change has become another major energy policy agenda requiring greenhouse gas emission reduction especially in the electricity generation and use sectors as major sources of emission. However, the effects of both market reform and climate change policies on electricity prices may be mixed. Although a deregulated electricity exchange market allows an electricity company to choose the least expensive generation source, costs of introduction of renewable energy have been added on to the electricity prices as governments' financial supports such as Feed-in-Tariff are introduced to cover high installation costs and reduce investment risks. In the chapter 2, we assumed that 3Es are independent criteria. However, electricity prices, one of the most popular indicators measuring the economic aspect of policy regarding electricity, are actually affected by energy policies on renewable energy, electricity market reform, climate change and other elements such as level of the development of economy and so on. Hence, the research focus shifts to the understanding of this interrelationship of energy policies centered on the electricity prices, in the era of increasing renewable energy and electricity market reform.

Based on this energy policy context, chapter 3 is dedicated to examine the following three main research questions. 1) Have electricity market reforms achieved lower household electricity prices? 2) Has the introduction of renewable energy increased household electricity price in the deregulated market? And 3) how to measure or model the different effect of market reforms and introduction of renewable energy on household electricity prices in a model? In order to examine these research questions, we constructed two novel panel data models. In these models, impacts and significance of multiple explanatory variables such as level of electricity market reforms, percentage of renewable energy and five other variables and a dummy variable for EU member countries are examined using internationally comparable data from 1991 to 2014 for seven selected OECD countries. The analysis suggests that lower household electricity prices is associated with the evolution of regulatory reform on the electricity market. It also concludes that the share of renewable energy in electricity generation is not statistically significant. Notable implication to energy policy is that, in theory, increasing renewable energy with low marginal generation costs can potentially lower electricity prices in the future in a deregulated electricity market that has a spot or dynamic electricity exchange market.

In this research, two different scientific approaches were employed and utilized to organize, analyze and propose mixed energy policy solutions related to electricity mix scenarios and electricity prices. In summary, applying these two scientific approaches enables quantification, comparison and analysis of different energy policies that are usually not comparable with similar metrics. The AHP model proposed to a reach a real decision-making policy decision and further development of the panel data model should be explored in order for the continuous scientific evaluation of the mixed energy policy.

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List of Publications

Chapter 2: Influence of Safety Risk Perception on Post-Fukushima Generation Mix and its Policy Implications in Japan
(Asia and the Pacific Policy Studies, vol. 3, no. 3, pp. 518–532. doi: 10.1002/app5.151)

Chapter 3: The impact of renewable energy on household electricity price in liberalized electricity markets: A cross-national panel data analysis
Utilities Policy, vol. 54, October 2018, pp. 96-106.

Chapter 1: Introduction

1.1 Introduction

Energy policy is one of the most important policy areas facing national governments. National governments, both developing and developed countries seek to ensure affordable, stable and accessible, environmentally acceptable energy that is available to its people although policy priorities and available policy measures are different in each country. Endowment of energy resources such as fossil fuel and renewable energy are so different in each country. Energy technologies vary with each nation and each country adopts a policy that depends on the level of technology and economic consideration of that particular country. Once energy technologies and facilities are deployed, it is often the case that the technology paths are locked based upon the energy infrastructure at large and it takes a long time to recover the investment costs of it. Geopolitical risks, natural and human disasters also have induced energy supply disruption and urged governments to respond to them. International concerted effort is also needed in some area of energy policy such as strategic petroleum reserves prepared after the oil shocks in 1970's among developed countries and greenhouse gas (GHG) emission reduction actions to tackle global warming.

Achieving energy policy goals requires balancing the different and often competing policies related to environmental protection, energy security, development of national economy and public safety, and on the other hand reaching agreement among various stakeholders whose interests sometimes conflict sharply with each other. It is essential that scientific approaches be applied to organize, analyze and propose rational solutions to controversial, mixed energy policy issues.

Stakeholders of energy policy are wide-ranging from community, regional and national level to supra-national integration organization such as EU, and international organization.

Energy policy thus has a feature of including multi-facet policy objectives and stakeholders by its nature.

So, there is often complicated trade-offs among energy policy objectives, such that a policy objective cannot be met at the same time with other policy objectives. A simple example is increasing coal use in electricity generation. Coal is an inexpensive and a widely available energy resource that scarcely induces energy security issues but its combustion can worsen public health condition through air pollution if the flue gas is not properly treated and it is also associated with the most GHG emission intensive energy source.

These kinds of trade-offs in energy policy requires an extensive comparison of values that cannot be compared using the same metrics, such as price and energy security versus environmental protection. Also, it requires examination of the impacts of different/alternative policy measures to the level of achievement of a policy goal.

1.2 World energy outlook: Growing energy consumption, transition to a cleaner energy society and progress of electrification

Figure 1.1 shows steadily growing world energy consumption by energy sources. Energy consumption has doubled in the last 30 years. As for the energy mix, transition to a cleaner emission energy society in ongoing. The use of coal based energy generations appears to have peaked. The use of natural gas has increased rapidly, as the US production and exports has increased. Asian countries have increased their imports due to lowering their CO_2 emissions and to lessen their air pollutions. The share of renewable energy is still limited compared to traditional energy sources, but rapidly increasing its share. However, in terms of environmental protection aspect of energy policy, CO_2 emissions from fuel combustion continues to grow, especially in Far East and other developing area of the world continue to grow as energy demand increases (Figure 1.2). Emission reduction both from developed and developing nations are needed to meet the Paris Agreement within the United Nations Framework Convention on Climate Change aiming to respond to the global climate change threat by keeping the global temperature rise this century well below 2 degrees Celsius above pre-industrial levels.

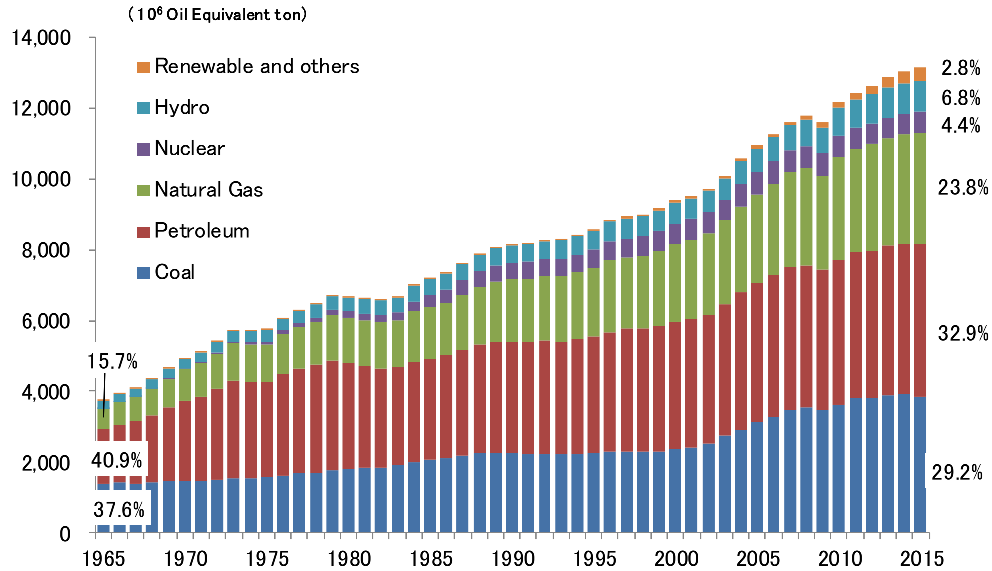


Figure 1.1 World energy consumption by primary energy source

Source: Energy White Paper 2017, Agency for Natural Resources and Energy (ANRE)

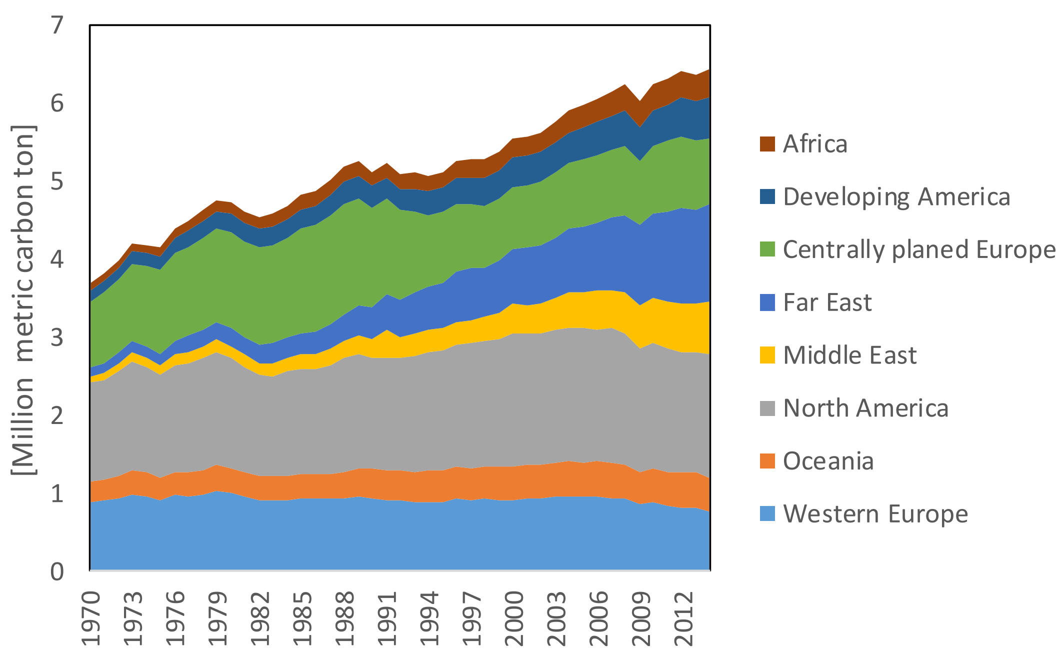


Figure 1.2 CO_2 emissions from combustion and cement production

Source: Global, Regional, and National Annual Time Series (1751-2014), Fossil-Fuel CO_2 Emissions. The Climate Change Science Institute, Oak Ridge National Laboratory

Electrification progresses all over the world (Figure1.3), meaning that more and more energy is being consumed to provide electricity. Electricity's feature of versatility and free-from-pollution at the point of use in the final energy consumption also enables to use more electricity in transportation and heating use, where combustion of fossil fuels has been a tradition. With regard to the portfolio of electricity mix, it is totally different in each country. Figure 1.4 shows the electricity mix of G7, Korea and China. Coal is widely used for electricity generation not only in China with a strikingly high 73%, but even in the G7 countries approximately 30-40 % of the electricity is derived from coal except for France, despite coal's high greenhouse gas emission intensity. Some of the countries have already switched to renewable energy (indicated as "others") as a major generation source.

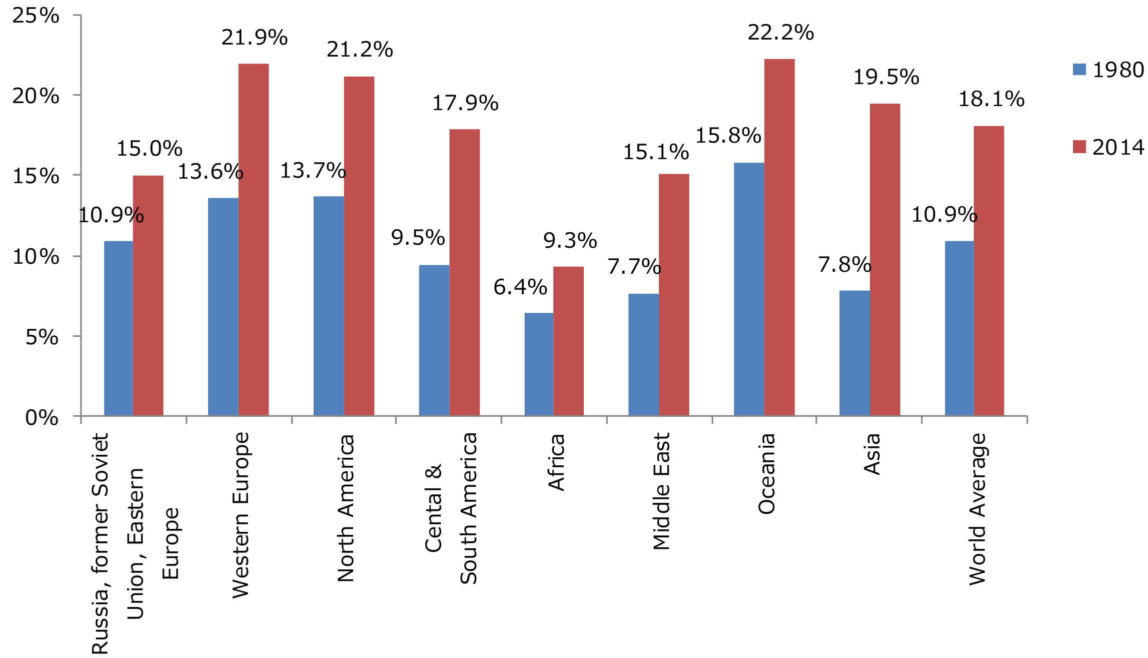


Figure 1.3 Electrifying rate by region

Note: Definition of electrifying rate: share of electricity consumption in final energy consumption

Source: World Energy Balance 2016, International Energy Agency (IEA)

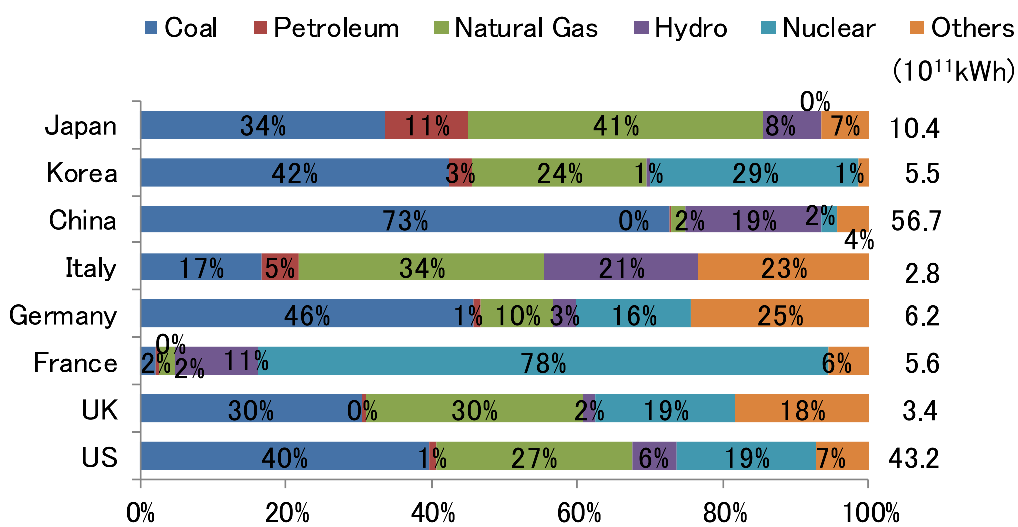


Figure 1.4 Electricity generation by energy source in selected countries (2014)

Source: Energy White Paper 2017, Agency for Natural Resources and Energy (ANRE)

Nuclear power had been viewed as a panacea energy source, since the oil shocks in 1970's in order to solve complicated trade-offs of energy policy. Compared to the oil based thermal-electric power plants that was a mainstream generation source in that time, nuclear power electric plants are considered to have desirable characteristic as an energy source. Nuclear power plants operate with small amounts of fuel at a high operational rates and thus are considered to be cost-efficient for power generation. Furthermore, the endowment of nuclear fuel is not concentrated in the Middle East as petroleum is, easily storable and there is a stable supply, less impact on environment in terms of air pollution and GHGs emission. On the other hand, repeated nuclear accidents such as the Three Mile Island Nuclear Power Plants in Pennsylvania in the United States in 1979 (accident with wider consequences, level 5 of the International Nuclear Event Scale (INES)), the Chernobyl Nuclear Power Plants in the Soviet Union in 1986 (severe accident, level 7), and the Fukushima Daiichi Nuclear Power Plant accident in Japan in 2011, (severe accident, level 7) have given society a clear warning on the potential nuclear safety risks that may occur with long-term radioactive contamination over a wide area once a serious accident happens.

Renewable energy has become another panacea from the view point of the environment, energy security (no supply disruption abroad), safety (no severe air pollution), and no GHGs emission nor potential radioactive contamination. Renewable energy is also a distributed energy that utilizes regionally endowed resources such as solar, wind and biomass and expected to create local employment. Furthermore, although renewable energy originally had relatively higher costs of generation compared to other sources of energy, it is no longer a big obstacle anymore with the rapid dissemination. Levelized costs of electricity (LCOE) of PV dropped by half between 2010 and 2014 and the most competitive utility scale PV project are now regularly delivering for just USD

0.08/kWh without financial support, compared to the range of USD 0.045/kWh to 0.14/kWh for fossil fuel derived electricity (International Renewable Energy Agency (IRENA), 2015). The introduction of renewable energy has been initially supported by governments through R&D sponsored programs, and followed by economic measures such as Renewable Portfolio Standard (RPS) that sets quantitative goals to introduce renewable energy, and also Feed-in-Tariff (FIT) system that operates based upon a government guarantee to purchase electricity generated by renewables energy at fixed prices. The policy measures of the national governments are shifting from a fixed-price FIT to market based auctions with more competitive conditions for the acquisition of renewable energy (IEA, 2017). Now, a virtuous circle occurs where increased introduction of renewable energy brings cost reduction in production and installation of generation facilities, technology improvement in generation efficiency and thus further increase in introduction of renewable energy. Also, renewable energy such as PV, wind and geothermal require no fuel, it means that these marginal costs are lower compared to the energy sources that require fuel. This is a remarkable feature of renewable energy when traded in a real-time electricity market typically established after deregulation of wholesale markets.

Turning attention to the energy outlook in Japan after the Great East Japan Earthquake and the Fukushima Daiichi nuclear accident in 2011, one can easily point out that loss of nuclear energy has been offset by energy saving and supplemented mainly by imported LNG (Figure 1.5 and Figure 1.6). Japan faced challenging energy policy management in meeting immediate demand without nuclear power and balancing energy goals of renewed importance of nuclear safety and its so-called traditional 3Es goals (<u>E</u>conomic growth, <u>E</u>nergy security, and <u>E</u>nvironmental protection) in the long-term. The latest statistics shows that the already low energy self-sufficiency rate in Japan dropped without quasi-domestic nuclear energy from 19.9% in 2010 to around 6 to 7 % after the accident (Figure 1.7) resulting from the above circumstances.

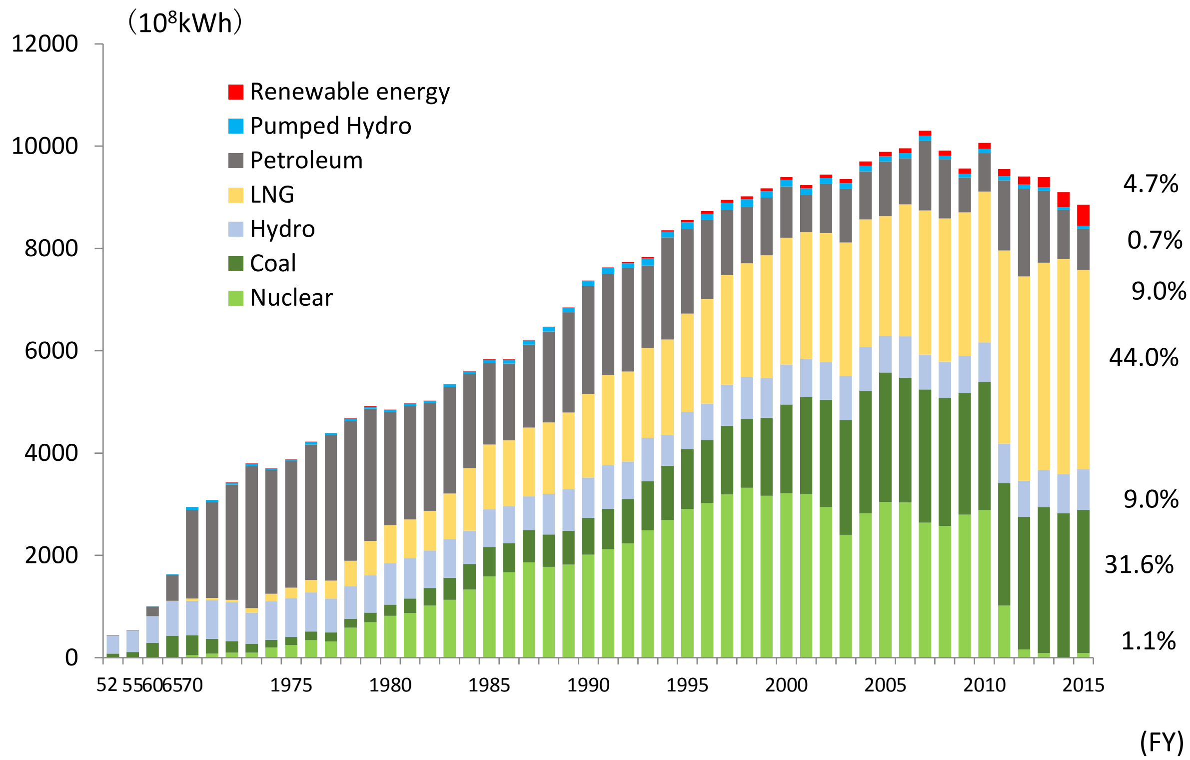


Figure 1.5 Electricity generation by energy source in Japan
Source: Energy White Paper 2017, Agency for Natural Resources and Energy (ANRE)

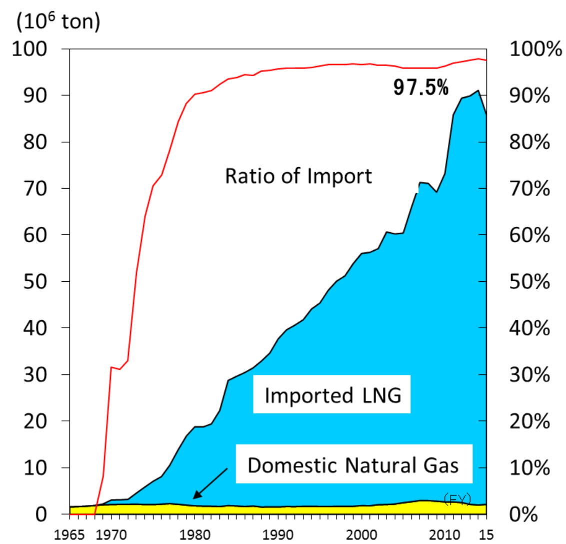


Figure 1.6 LNG import in Japan
Source: Energy White Paper 2017, Agency for Natural Resources and Energy (ANRE)

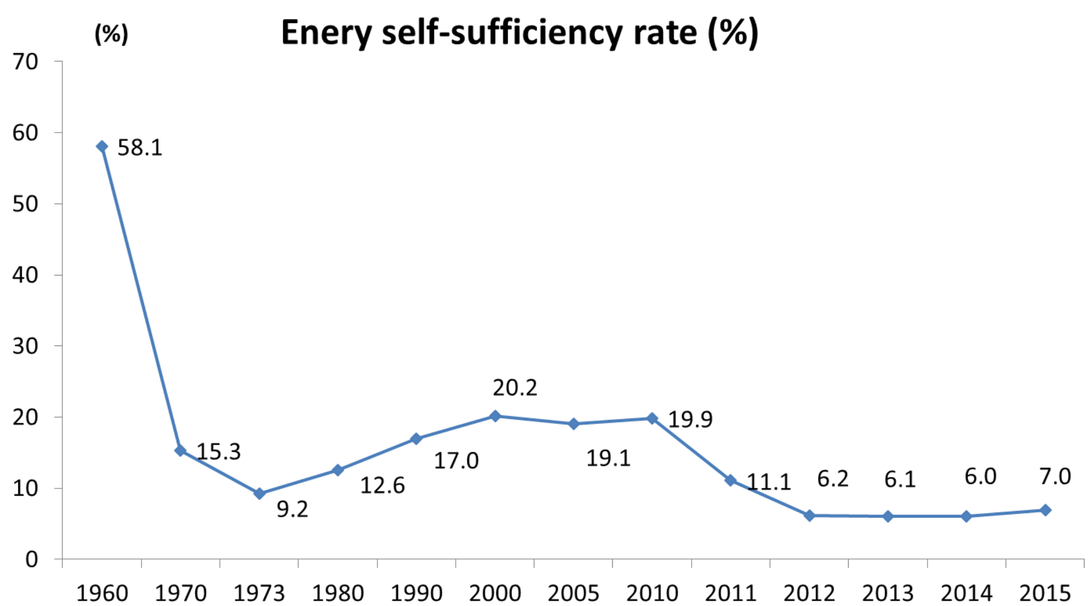


Figure 1.7 Energy Security in Japan – Self-sufficiency rate
Source: Energy White Paper 2017, (ANRE)

1.3 Two research themes

As the world final energy consumption shifts more to the electricity, energy policy on electricity has become more important – what is the best energy mix to ensure affordable, accessible, acceptable electricity available to the nation, at what price?

One of the toughest challenges to the recent energy policy on electricity is the Japan's choice of future electricity mix after the Fukushima accident.

Another theme is the electricity prices that are affected by various elements of energy policy such as regulation and market reforms, and the level of prices also influence electricity consumption, investment and energy saving efforts.

Both themes are typical in energy policy to deal with trade-offs of multiple policy objectives that are difficult to measure using the same metrics.

Providing scientific evaluation of renewable energy is a common theme in Chapter 2 and 3. Policy measures encouraging introduction of renewable energy such as the FIT system are being utilized due to expectations that renewable energy is clean and becoming a more sustainable energy source. However, level of renewable energy introduced differs from country to country. It remains marginal in Japan, while it already serves as a substantial part of electricity in some European countries like Germany, Italy and UK. OECD member countries have common energy policy objectives i.e. stable and economically rational supply of energy and reduction of GHG emissions, but have different electricity mix and electricity pricing due to each country's situation relating to the endowment of natural energy resources, energy supply system like electricity grid and geopolitical situation.

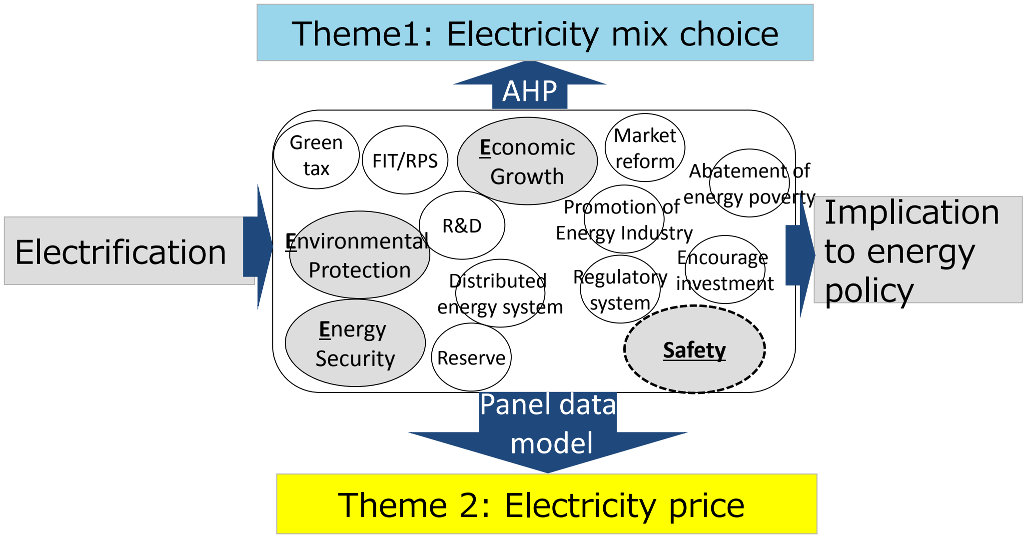


Figure 1.8 Proposed model showing overlapping relationships between electrification, electricity price, energy policy and electricity mix outlining this thesis.

In this thesis, the first chapter gives a general overview of world energy outlook and fundamental research topics, the subsequent two chapters are dedicated to the examination of two major energy policy areas of electricity generation mix and consumer electricity prices in detail in the second and third chapters.

These two major aspects of energy policy on electricity are examined by using different scientific approaches (Figure 1.8).

1) Energy mix aspect: application of Analytical Hierarchy Process (AHP) to decision-making to examine how priorities and different values influence the decision making of optimal electricity mix. Renewable energy is evaluated as one of the energy sources in the electricity mix.
2) Electricity price aspect: application of panel data models to examine the influence of the multiple determinants of electricity prices and their impacts. Renewable energy is then examined as in a policy phase – how does the

percentage of renewable energy introduced impact electricity prices compared to electricity market reform policy and other determinants of electricity prices.

The final chapter concludes with overall conclusion, achievement and future work. Implications of this research on Japanese energy policy are also explored based upon these two research themes.

Chapter 2: Influence of Safety Risk Perception on Post-Fukushima Generation Mix and its Policy Implications in Japan

2.1 Introduction

There has been an on-going debate in Japan on its energy policy, lasting several years, especially regarding the electricity generation source mixture (generation mix) after the Fukushima Daiichi nuclear power plant accident in March 2011. Although the government has made notable progress on its new energy policy, such as an accelerated utilization of renewable energy by the introduction of a Feed-In-Tariff system and enhanced nuclear safety regulations, the continued use of nuclear energy remains a controversial issue. The 3.11 earthquake brought a paradigm shift in energy policy to emphasize public safety as a precondition, in addition to the so-called "3Es" of **e**nergy security, **e**conomic growth (affordability) and **e**nvironmental protection as an unconceivable catastrophic nuclear accident became a reality. Consensus-based decision-making, which is used in Japan, faces increasing difficulty reaching a compromise decision when differences in public opinions are far apart, particularly as related to nuclear energy utilization. As Japan seeks more non-oil fossil fuel alternatives in its energy mix today and in 2030, its policy will profoundly affect its energy supply and demand in Asia and the Pacific region because of its large economy. For example, Japan's import of fossil fuels (crude oil, coal, LPG and LNG) amounts to approximately USD 224 Billion in FY 2014 and 34% of it is imported from the Asia and the Pacific region (Ministry of Finance 2014). Safety regulations and public communication on nuclear energy have also become a challenge for the government that is promoting nuclear energy, especially in the Asia Pacific region where construction of new nuclear power plants is concentrated (World Nuclear Association 2015).

In this paper, we present an evaluation of the optimal generation mix for Japan with two opposing views on safety incorporating an Analytical Hierarchy Process (AHP), a broadly used decision-making method. In the first section, after briefly reviewing the post Fukushima Japanese energy policy in order to assess the historical role of nuclear energy in achieving the 3Es policy goals and how the policy has been challenged by the public opinion after the disastrous accident, special attention is paid to examine the increasing importance of public opinion in energy policy dialogue with renewed emphasis on safety regardless of the 3E goals. Then, a three-layer AHP model with two opposing views on safety is introduced in the second section with results in the third section indicating that the highest nuclear power proportion scenario (20% nuclear in the generation mix) is the most appropriate if safety is evaluated based upon scientific measurement of risks. Although this may appear contradictory to the public opinion of eliminating nuclear energy in Japan, the statistically low human fatalities, when scaled to power generated, indicates that the 20% nuclear power scenario is the safest policy alternative. The final section concludes with policy implications.

2.1.1. Re-Establishing Energy Policy after Fukushima: 3Es+Safety

The Fukushima nuclear accident drew public attention world-wide to energy policy as never before, resulting in rethinking of the importance of energy power safety related to the electricity mix. The accident and the following shut-down of all the nuclear reactors for legally mandated safety inspections made a fundamental review of the role of nuclear energy in Japan's energy mix inevitable.

However, reaching a new nation-wide policy consensus was not easy as nuclear energy has become a panacea in Japan to satisfy the 3Es. Nuclear energy was increasingly a principal and realistic option after the two oil shocks in 1970s when renewable energy technologies were neither cost effective nor available for large-scale commercial use. In the1990s, energy policy shifted to balancing environment protection and economic growth. Nuclear appeared to be the best option for the energy mix in order to both meet the 6% GHG emission reduction obligation under the Kyoto Protocol and to lower electricity price in the deregulated wholesale electricity market.

Nuclear energy was also expected to contribute to improve Japan's dependency on foreign fossil fuel as it is thought as a quasidomestic energy source because of its storability and recyclability. In the 2000s, the Japanese government enacted the Basic Act on Energy Policy (Act No. 71 of 2002) to show the direction of the energy policy in an era of increasing uncertainty and once again nuclear energy had been given a high priority for energy security. The Act also requires the government to establish and review a Basic Energy Plan (BEP) every three years. The BEP 2010, which is the third, placed special emphasis on increasing nuclear power generation to achieve higher energy security aiming to build fourteen new or additional nuclear reactors with the overall plant capacity utilization rate at approximately 90% by 2030, resulting in aiming for a 50% share of nuclear electricity generation by 2030 (Advisory Committee on Natural Resources and Energy 2010).

However, minor nuclear accidents even before the Fukushima nuclear accident had discouraged the prospects of further introduction of new nuclear power plants. Experts pointed out that these targets in BEP 2010 were quite challenging even before the Fukushima nuclear accident (Duffield & Woodall 2011).

Overall, expectation on nuclear power in the energy mix was at its maximum at the time of the BEP 2010 which was concluded just nine months before the 3.11 earthquake. Nuclear energy accounted for approximately 30% of the generation mix just before the accident. As a consequence of the 3.11

earthquake, the immediate electricity shortage crisis happened with the loss of approximately 26 GW (40%) of the generation capacity including nuclear, thermal and hydro in the Tokyo and North eastern Japan area where the earthquake damage was the most severe. After it calmed down by mid-April 2011 (ANRE 2011), the Government initiated a fundamental review of the role of nuclear in energy mix backed by strong nuclear-free public opinion. The government proposed three different generation mix scenarios – achieving 0%, 15% or 20-25% nuclear shares in electricity generation by 2030 in June 2012 and the public discussion on generation mix intensified. During the summer of 2012, the government held eleven regional meetings nationwide to deepen public understanding on the three scenarios. In addition, public opinion polls were also introduced for the first time in the Japanese energy policy making process to provide input on selecting the three scenarios. The poll showed strong support for the nuclear-free scenario at 49.8% and strong opposition to the nuclear 20-25% option at 41.8%. As for the importance of criteria in choosing energy, 67.5% answered "securing safety" is the first priority, followed by "securing stable supply of energy" at 16.7%, "protection of global warming" at 9.3% and "cost" at 4.5% (Committee for the deliberative poll on policy options of energy and the environment 2012).

After these public discussions, the government decided on September 14, 2012 the Innovative Strategy for Energy and the Environment aiming to phase out all the nuclear power plants by 2030s with this strong public support. However, the strategy gave a mixed message – it did not plan new and additional nuclear power plants but allowed continuing the nuclear fuel cycle policy which implies continued use of nuclear energy (The Energy and Environment Council 2012). In response to the criticism by pro-nuke stakeholders to the inconsistent nuclear policy, the cabinet corrected its course of phasing out nuclear power plants just five days after the announcement of the Innovative Strategy by deciding another policy document merely pledging to "review and re-examine energy policy with flexibility taking into account the Innovative Strategy in a responsible manner with related local governments, the international community and others, and obtaining understanding of the Japanese public", without establishing any nuclear-free scenario (Cabinet of Japan 2012).

After the historically pro-nuke Liberal Democratic Party (LDP) returned to power, LDP's Abe administration finally decided on the new BEP in 2014. Nuclear energy is once again positioned as an important base load power source in the plan (ANRE 2014). Although safety is considered as a presumption of energy policy, how to measure the safety of energy use was not discussed in the BEP 2014. The future portfolio of generation mix, which is 22-24% of renewable energy, 20-22% nuclear, 27% LNG, 26% coal and 3% petroleum was finally determined in July, 2015. For the enhancement of nuclear safety, the new Nuclear Regulation Authority (NRA) established a renewed safety regulation for nuclear power plants. In July 2013, aiming to be "the world toughest standard", new regulatory standards against natural disasters such as earthquake, tsunami and volcanic eruption were introduced. Countermeasures are also required to prevent core damage, maintain containment integrity and suppress radioactive materials dispersion even if a severe accident occurs (NRA 2013a, 2013b). The NRA gave its first approval for restart of nuclear power plant for operation based on the enhanced safety regulation in July, 2014. The annual poll taken after the NRA's first approval by the Japan Atomic Energy Relations Organizations (JAERO), which has been conducting nation-wide polls on nuclear energy since 2006, showed an increased understanding of usefulness of the nuclear power generation as 41.7% responded positively and 19.0% responded negatively. The percentage of opposition dropped sharply compared to the poll from the previous year and this may indicate a gradual shift in public sentiment towards nuclear energy, although 47.8% answered that nuclear power plants should be used for a while but abolished gradually. The poll after the accident indicates the necessity to strengthen risk communication, safety regulations and points out the need for greater information disclosure (JAERO 2014).

Meanwhile, from the viewpoint of the 3Es, the shutdown of all the nuclear power plants has had a huge impact on economy and CO_2 emission. LNG power generation has taken over most of the loss of electricity generation by nuclear energy, in fact LNG imports almost doubled to USD $73.6 Billion in 2014 from USD 39.9 Billion in 2010, severely burdening economic growth. The renewed dependence on imported LNG and other fossil fuels was recognized as a new energy security risk as dependency on foreign energy resources marked a record high at 94% in 2013 up from 80.1% in 2010 (ANRE 2016). CO_2 emission from energy use also increased 8.4% in 2013 compared to 2010 (Ministry of Environment 2015).

2.1.2. Increasing Importance of Public Opinion in Energy Policy Decision Making

Having reviewed reestablishment of the post-Fukushima energy policy, what has made public opinion more important in Japan's energy policy decision making? First of all, it is considered that consensus of nuclear facility hosting local governments is required for the restart of the nuclear power plants. The rationale behind this is a Safety Agreement concluded between nuclear power plants operator and the hosting local government. A Safety Agreement typically stipulates the establishment of a communication system, on-site monitoring by local government, prior consultation and consent when facilities are renewed and added to protect health and safety of the local community. It is not a legal requirement, but a gentlemen's agreement established in order to maintain mutual trust (Sugawara 2010). In addition to that, after the Fukushima accident, local governments within 30 km of a nuclear facility now need to devise evacuation plans for their residents in the event of a major accident. As evacuation became a reality even in municipalities located further than 30km from the Fukushima Daiichi where radioactive materials were scattered after the accident, democratically elected governors of municipalities hosting nuclear facilities have to be aware of public opinion more than ever. Second, the nuclear accident has broadened the stakeholders of nuclear energy issue from the local people living in the municipalities hosting the nuclear facilities to residents nationwide. Even metropolitan Tokyo that is 225 km away from the Fukushima Daiichi and is populated by more than 40 million people suffered low level radioactive materials scattered by wind after the hydrogen explosion in the power plants. 178,000 people originally living in the local vicinity of nuclear power plants are still evacuated as of January 2016 (Reconstruction Agency 2016). Such geographically wide range of influence and long-term damage to the local community due to scattered radioactive materials was hard to imagine but became reality. In addition to that, the Fukushima accident made it clear that people have to pay more for electricity if nuclear was not used. Average nationwide electricity price has increased approximately by 25% on an average per household and 40% for industry in FY 2014 compared to FY 2010 mainly due to the increased fuel cost to supplement the loss of electricity generation by nuclear energy (ANRE 2016). Increased use of renewable energy due to the newly introduced Feed-in-Tariff system also has contributed to the increase of household electricity bill. Future economic burden for the decades-long decommission of damaged power plants and rehabilitation of Fukushima local area are also expected. Individuals, who originally were beneficiaries of nuclear energy, have become defrayer or adversaries of nuclear energy. Third, the so called “nuclear village” was unable to respond to the public expectation on the governance of the nuclear energy policy. Kingston (2013) explains that "nuclear village" is the commonly used word in Japan to refer to the institutional and individual pro-nuclear advocates in nuclear industry, government bureaucracy, Diet, media and academia. The village shares a common mentality and sensitivities about nuclear energy, ostracizing naysayers and critics and denying them the access and benefits that "village members" enjoy. It is not the purpose of this paper to discuss the reality of the nuclear village, but the background hypothesis in this paper is that public opinion becomes more important and such closed nature of nuclear energy policy has retarded public debate and left governance of the nuclear energy policy to the village itself. Mie Ooba, one of the members of the former Japanese Nuclear Committee once spoke as testimony in a committee in the House of Representatives that although it is natural that experts in some areas form a kind of "village", nuclear energy is technologically so specialized and such kind of a very closed community of experts is problematic because it does not communicate outside the "village" (The House of Representatives 2011). The process of reestablishing the new BEP revealed the difficulty in reaching a national consensus on a generation mix. Meanwhile, public opinion remains skeptical to the full continuation of nuclear electricity generation in spite of the Japanese government's efforts to enhance nuclear safety. As safety becomes an important prerequisite for public support of continued nuclear energy use, the government need to balance the trade-offs of safety, costs, GHGs emission and security of supply of having nuclear energy in energy mix. There is a clear need to systematically evaluate generation mix scenarios, trade-offs between 3Es and safety criteria and influence of opposing risk perceptions for fact based, realistic decision-making on the optimal generation mix.

2.2. Methods

In this study, a novel three-layer AHP model was developed to examine the three generation mix scenarios proposed by the Japanese Government in 2012 with two opposing views on safety and their sensitivity analysis.

2.2.1. AHP and its Application to Energy Policy Decision Making

AHP is a decision-making methodology which consists of hierarchically disposed layers, from a goal layer, criteria layer, and down to an alternative layer proposed by Thomas Saaty (Saaty 1980). AHP has numerous merits for use in decision making methodology. First of all, a decision maker can give weights by pairwise comparison to social or political values that are not measured in economic or numeric terms and thus compare the importance of two elements measured based upon different values such as value of environmental protection versus energy security, or energy security versus safety. Second, a set of such pairwise comparisons enables decision makers to prioritize cardinal ranking rather than ordinal ranking, making it easier to check the consistency of the prioritization. Third, determination of weights and consistency checking by comparison of matrix eigenvectors and eigenvalues has a strong mathematical background (Saaty 1980; Kinoshita 2000).

The basic methodology of the AHP is as follows. First, the objective of the model is set and appropriate criteria and alternatives in respective layers are chosen. Then, the elements in each layer are compared in pairs by giving a weight varying such as from 1 (equally important) to 9 (absolutely more important) with regard to each item in the upper layer. This set of pairwise comparisons results in the construction of a matrix-based model, and weights of the elements in the criteria and alternative layer are derived as the eigenvectors of the comparison matrices. The consistency of the pairwise comparison is checked with the Consistency Index (C.I.), defined as (λmax– n) /

(n - 1), where n is the number of the elements in the layer and λmax is the maximum eigenvalue. AHP has been widely used for planning, resource allocation and conflict resolution in various fields including economic prediction, marketing and foreign policy and the most used multi-criteria decision making analysis (MCDMA) methodology for various energy related decision making because of its theoretical basis and the simplicity in application (Wang et al. 2009). One of the most remarkable applications of AHP to an actual energy policy decision-making scenario was a case in Finland. AHP was officially used to support a decision on the introduction of a new nuclear power plant in Finnish Congress showing a preference for nuclear energy in terms of reducing air pollution (Hamalainen 1990).

There have been many other AHP cases applied to the energy policy issues. Lee et al. (2007) examined Korean national energy policy focusing on energy efficiency and GHGs reduction plan using a four-layer-AHP on 34 energy technologies. Noguchi and Takahata (2008) examined seven alternative policy scenarios for an existing Japanese local government to introduce renewable energy with a four-layer-AHP. However, these prior studies using AHP did not take into account decision making of the post-Fukushima generation mix. Hence, it is of merit to apply AHP to the above scenarios with a mixture of economic and non-economic values and analysis of trade-offs among criteria to make an objective decision. Alternatively, Japanese society's consensus based decision making approach experiences difficulty in reaching a decision when wide gap exists in opposing views on safety, where consensus is necessary for all to support the decision.

2.2.2. Evaluation of Safety

In this study, we introduced two opposing safety views. One is the nuclear-free preference, "the less nuclear, the better and the safer" view and the other is a scientific measurement of safety risk. As no index or quantifiable measurement on the safety criterion was proposed in the BEPs commonly applicable to the different energy resources, we adopted fatalities per GWeyr (Gigawatt-year of electric power) as a scientific measurement of safety risks to evaluate different energy resources based on literature review of methodologies on quantitative evaluation of safety of different energy resources. Hong et al. (2013) estimated direct damage and external costs of fatalities, injuries and evacuations for Japanese future energy mix scenarios after the Fukushima accident in a non-AHP MCDMA model, showing that the 35% nuclear scenario had the lowest external cost of USD 14.36/GWh, the nuclear-free scenarios had the highest cost of USD 21.86/GWh, and the current energy mix is USD 22.96/GWh. They noted that nuclear is statistically safer than other energy resources and concluded that discarding nuclear energy is not an appropriate policy choice for Japan to enhance public safety. The Science Council of Japan (2013) proposed another approach to measure safety in energy use by evaluating environmental damage using multiple aspects: air pollution by NOx, SOx and particles, the effect on the ozone layer depletion, climate change by GHG emissions and emission of radioactive materials. However, no single and integrated safety index evaluating different energy resources was proposed.

Among others, the OECD/Nuclear Energy Agency (NEA) and the Intergovernmental Panel on Climate Change (IPCC) cite the Energy-related Severe Accident Database (ENSAD) of the Paul Sherrer Institute (PSI) in Switzerland for quantitative comparison of risks in energy use (OECD/漏れ NEA 2010; IPCC 2012). The PSI introduced seven criteria for the definition of severe accident in energy use as follows (Paul Sherrer Institute n.d.):

1) At least five fatalities

2) At least ten injured

3) At least 200 evacuees

4) Extensive ban on consumption of food

5) Releases of hydrocarbons exceeding 10,000 ton

6) Enforced clean-up of land and water over an area of at least 25 km^2

7) Economic loss of at least five million USD (2000)

IPCC estimated safety risks of different energy resources used in electricity generation based on the data and definition of the ENSAD (Table 2.1) showing that nuclear and renewable energy displays lower rates of fatalities per GWeyr for OECD countries compared with the fossil fuels. These figures include only the accident fatalities and do not include other risks such as health damage by pollution. International Atomic Energy Agency (IAEA) has developed detailed and extensive accumulation of knowledge on risk analysis on nuclear energy. The Nuclear Regulation Authority, the Japanese nuclear regulatory organization established after the Fukushima Daiichi accident in September 2012 also relies on IAEA's rich store of knowledge of the nuclear risk analysis knowledge. However, these risk analysis are not adopted in this thesis as they are very much specific to nuclear energy and not comparable in the same metrics to the risks associated with other energy source of electricity generation such as thermal power, hydro and renewable energy.

Table 2.1 Fatalities per GWeyr for Energy resources†

Coal	0.12
Oil	0.0932
Natural Gas	0.0721
Hydro	0.0027
Nuclear	0.00726
PV	0.000245
Biomass	0.0149
Geothermal (Enhanced Geothermal System)	0.00174
Wind (onshore)	0.00189

†GWeyr is Gigawatt-year of electric power. 1GWeyr = 8.76 * 109 kWh
Wind data is for onshore in Denmark
Note: these figures are for OECD countries, include only the accident fatalities and do not include other risks such as health damage by pollution.
Source: Renewable Energy Sources and Climate Change mitigation, Special Report of the IPCC (IPCC 2012)

The AHP model in this research adopted these IPCC data as a safety index by carefully considering the following points. First, the data are comparable among different energy resources with a single scaling of fatalities per GWeyr. Second, among many risk indices such as human fatalities, casualties and evacuation, the fatality rate is typically the most reliable measure and accurate due to the available data (IPCC 2012). Third, the fatality rate on nuclear energy is available for the Generation II nuclear reactors and compatible with the four reactors at Fukushima Daiichi that are all boiling water type, Generation II reactors. Fourth, published in 2010, the data do not take into account the Fukushima Daiichi Nuclear accident. On this point, the accident is not expected to affect the risk measured with fatalities fundamentally, although the record of the accident shows three fatalities in the Fukushima Daiichi site that is not regarding to the explosion of the reactors (NISA 2011).

Based on the data on the Table 2.1, our estimate indicates that the nuclear 0% scenario explained in the next section has the highest safety risk of 0.05935 [fatalities/GWeyr], followed by the nuclear 15% scenario's 0.05135 and the lowest safety risk of the nuclear 20% scenario's 0.04666. Since the nuclear 0% scenarios uses the largest amount of the top three higher-fatality energy resources (coal, petroleum and natural gas) among the three scenarios, it consequently results in a higher fatality rate and is the least safe.

2.2.3. AHP Model for Decision Making on Post-Fukushima Generation mix

The AHP model in this research consists of three layers: the objective (goal) layer as the top level, the criteria layer as the second level and the alternative layer for policy options as the bottom level as outlined in Figure 2.1. All layers and elements in a layer are assumed to be independent. The description of the model is below.

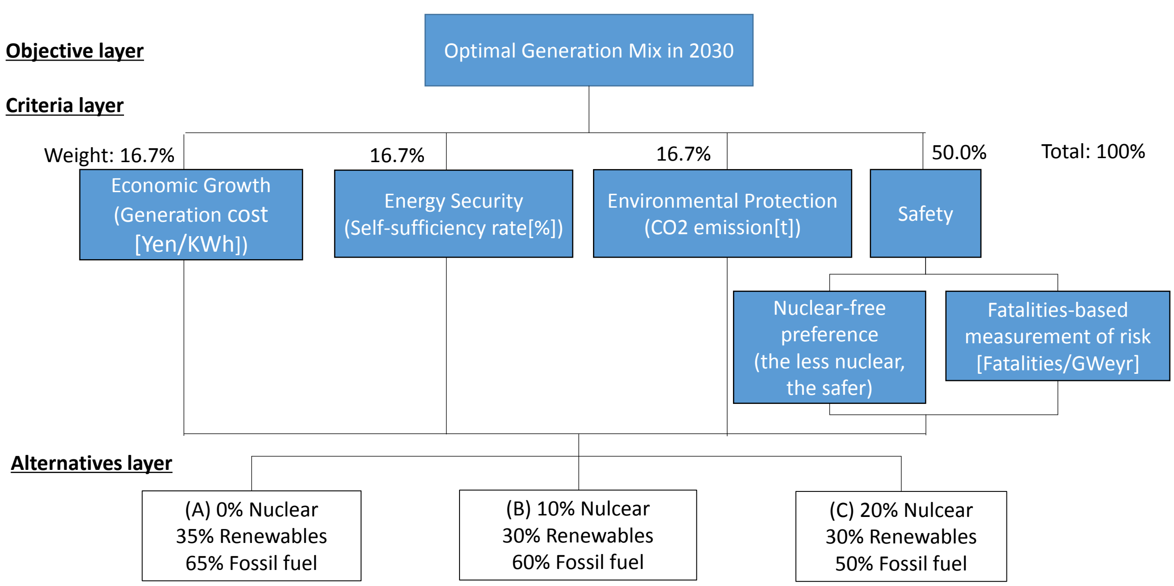


Figure 2.1 AHP model for optimal generation mix

2.2.3.1. Objective (goal)

The goal of this AHP model is to choose an optimal generation mix scenario in 2030 from the three alternative scenarios proposed by the Japanese government in 2012.

2.2.3.2. Criteria and Their Measurement

The model has four elements in the criteria layer: economic growth, energy security, environment protection and safety. To make the measurement of these criterion objective, we used data already published by the government for the evaluation of 3Es in the “Policy options for energy and the environment” in June 2012 (NPU 2012a). Although there are potentially various measurements of each to the 3Es, the most commonly used measurement in the course of the generation mix discussion in Japan were selected. As for the safety index, two different measurements for safety were proposed to compare opposing views. The criteria details are as follows:

(i) Economic growth: measured by estimated generation cost for each alternative scenario [yen/kWh]. Note that the government also used the following three other measurements for economic growth; total investment cost for constructing grid system additionally required for each scenarios [Trillion yen], electricity bill of an average household [yen/month] and estimated real GDP in 2030 [Trillion yen]. However, it is justifiable to adopt the estimated generation costs rather than other three measures for the analysis in this AHP model because all of these measurements support higher percentage of nuclear scenario that is less expensive because the estimated generation costs calculated based upon the total life cycle cost of electricity generation including investment cost, which is also less expensive with higher percentage of nuclear, and eventually affect the estimated real GDP. In a pairwise comparison in an AHP model, if the order of importance, such as nuclear 20%>nuclear

15%>nuclear 0% is the same for a criterion, the model gives the same tendency of weight distribution to each scenario in accordance with the order of importance.

(ii) Environmental protection: measured in estimated GHGs emission reduction in 2030 compared with 1990 for each alternative [%]. The government evaluation also has two other criteria for the environmental protection, namely the ratio of non-fossil fuel [%], that is equal to (100% – percentage of (nuclear + renewables)), and the coal versus oil ratio in thermal power generation as shown in the Table 2.2. It is also justifiable only to adopt the estimated GHGs emission reduction by two points. First, GHGs emission reduction is a part of international commitment for climate change and thus a high priority is given to it compared to the other two measurements. Second, both the ratio of non-fossil fuel and the coal versus oil ratio in thermal power generation will improve in the case with higher percentage of nuclear energy, thus resulting in the same tendency in supporting environmental protection with the criterion of the GHG emission reduction.

Table 2.2 Details of three generation mix scenarios proposed by the Japanese Government in 2012

	Criteria	2010	2030 (A)Nuclear 0%	2030 (B)Nuclear 15%	2030 (C)Nuclear 20% ‡
Generation mix	Nuclear	26%	0%	15%	20%
	Renewable Energy	10%	35%	30%	30%
	Photovoltaic		7%	7%	7%
	Wind		9%	7%	7%
	Hydro		12%	11%	11%
	Geothermal		3%	2%	2%
	Biomass		4%	3%	3%
	Thermal	63%	65%	55%	50%
	Coal	24%	21%	20%	18%
	LNG	29%	38%	29%	27%
	Oil	10%	6%	5%	5%
Energy security	Dependency on fossil fuel	63%	65%	55%	50%
	Import of fossil fuel [Trillion yen]	17	16	16	15
Environmental protection	GHGs emission reduction compared to 1990		23%	23%	25%
	Ratio of non-fossil fuel	37%	35%	45%	50%
	Coal vs. oil ratio in thermal power generation	1 : 1.2	1 : 1.8	1 : 1.5	1 : 1.5
Economic growth	Generation cost [yen/kWh]	8.6	15.1	14.1	14.1
	Grid system [Trillion yen]		5.2	3.4	3.4~2.7
	Electricity bill of an average household [yen/month]	10,000			
	Simulation by NIES		14,000	14,000	14,000
	Osaka Univ.		15,000	14,000	12,000
	Keio Univ.		21,000	18,000	18,000
	RITE		20,000	18,000	18,000
	Estimated real GDP [Trillion yen]	511			
	Simulation by NIES		628	634	634
	Osaka Univ.		608	611	614
	Keio Univ.		609	616	617
	RITE		564	579	581

Note that the alternatives (a) nuclear 0% option is with additional measures and

(c) was originally proposed as in the range of 20-25% nuclear, but in this paper a 20% share of nuclear is used for both model simplicity and because of the difficulty of using nuclear at as high a level as before the 3.11 incident.

NIES: National Institute for Environmental Studies

RITE: Research Institute of Innovative Technology for the Earth

Source: Policy options for energy and the environment (NPU, 2012a).

Renewable energy related materials (NPU, 2012b).

(iii) Energy security: (1 – rate of dependency on fossil fuel in energy resources for electricity) for each alternative [%]. Japan imports almost all its fossil fuel, and (1 –rate of dependency on fossil fuel) is an approximation of the self-sufficiency rate. The government also proposed import of fossil fuel [Trillion yen] as measurement of energy security. Again, this has also the same tendency that the import of fossil fuel will decrease with the higher percentage of nuclear energy.

(iv) Safety:

(1) Nuclear-free preference measured by the percentage of nuclear energy. This view has been taken by a majority of the Japanese public after the accident due to perceived safety concerns (risk) as discussed in the first section.

(2) Fatalities-based measurement of risks measured by fatalities per Gweyr due to severe accidents as estimated in the section 2.2. This measurement should be regarded as more scientific and reliable method based on the published literature.

2.2.3.3. Alternatives

Three alternatives for generation mix scenarios in 2030 were proposed by the National Policy Unit (NPU) of the Japanese Government (NPU 2012a). The summary of three scenarios is as below:

(a) 0% nuclear with 35% renewables and 65% fossil fuels

(b) 15% nuclear with 30% renewables and 55% fossil fuels

(c) 20% nuclear with 30% renewables and 50% fossil fuels

The details of each scenario and measurements for criteria are shown in Table 2.2. These scenarios were provided based on the thorough discussion and the report by the Cost Verification Committee, Energy and Environment Council established in the Cabinet Secretariat on the electricity generation costs and feasibility of each energy source for electricity generation (Cost Verification Committee, Energy and Environment Council, 2011). The main points to be mentioned here are how various costs associated with nuclear energy and feasibility of introduction of renewable energy were treated in this report. The stance of the report is that the costs are fluid as the costs for response to the Fukushima Daiichi nuclear power plant had not yet fixed at the time of the committee's discussion, and the nuclear fuel cycle policy after the accident and technology improvement of renewable energy and mass production effects are calculated with some assumption. Overall cost estimation is undertaken as model plant basis assuming a standard plant with an operational rate, a lifetime of operation and a discount rate for each energy sources for electricity generation such as coal, petroleum, natural gas, nuclear, PV, wind, geothermal, hydro and so on. Among others, costs associated with nuclear energy have a feature to include social costs for response to accidents (damage and additional safety measures), decommissioning costs, policy costs such as subsidy for encouraging location of nuclear power plants and nuclear fuel cycle costs, in addition to the usual calculation of generation costs consists of fuel costs, operation and management and construction costs. In the committee's report, the operational rate for a model nuclear power plant is assumed at 70% with lifetime of 40 years and discount rate of 3%. Those are moderate assumption yielding a higher costs estimation compared to the example of international costs estimation by OECD 2015 model at 85% of operational rate, 60 year-lifetime, and discount rate of 5% (OECD Nuclear Energy Agency (NEA) and International Energy Agency (IEA), 2010). At the time point of the committee's discussion, the Cost Verification Committee estimated the total damage costs of the Fukushima Daiichi accident to be 5.8 trillion yen.

It is also important to mention how the feasibility of introduction of renewable energy were considered in the committee's report. The committee distinguish the following three types of dissemination potential of renewable energy, and adopted the second definition "introduction potential based" estimation.

1) Endowment based, such that theoretically estimated from such as area where physically able to install PV panels, average wing speed and rate of flow of the river

2) Introduction potential based, such that excluding the points from the 1) above where development of renewable energy is not possible due to natural reason (elevation and inclination) and/or regulatory reason (natural park, forest reserve that development were limited by regulation), and

3) Economically feasible introduction potential based, where the introduction of renewable energy is economically feasible among the 2) above.

For instance, Japan has the world third biggest geothermal reserve as endowment based (International Renewable Energy Agency (IRENA)). However in the introduction potential based, utilization is limited because about 80% of the sources are located in the natural parks area (Japan Oil, Gas and Metals National Corporation (JOGMEC), 2015). As a result, Japan's capacity of geothermal electricity generation facilities is the world 10^{th} place, with only 2.2% of the country's geothermal endowment is utilized, compared to Iceland that has the world 9^{th} geothermal electricity generation capacity but 11.5% of its geothermal endowment is utilized (Japan Oil, Gas and Metals National Corporation (JOGMEC), n.d.). Note that the Ministry of Environment worked for clarification of the regulation on the treatment of geothermal inside national parks in order to encourage proper development of geothermal energy and issued notifications in 2012 and 2015 (Ministry of Environment, 2015). Another example of regulation on renewable energy is regulation by municipal governments. With the expansion of PV panels and wind turbines introduced after the Feed-in-Tariff system in 2012, some municipal governments have enforced regulation on introduction of renewable energy for the purpose of conservation of landscape, green zone preservation and disaster prevention, requiring prior notification or permission for installation of renewable energy facilities (NPO Corporation PV generation facility network, 2017).

Pairwise comparison

In this three-layer-AHP model, two different levels of pairwise comparisons are conducted between the objective layer and the criteria layer, and the criteria layer and the alternatives layer.

(i) Pairwise comparison of criteria with regard to the decision making goal

Table 2.3 shows the pairwise comparison among the four criteria with regard to the goal of choosing an optimal generation mix goal for 2030. Assuming the weighting for the safety criterion has become higher than before the 3.11 incident, the safety criterion is given more importance than the other three criteria at 50%, and a sensitivity analysis is undertaken in the following section to see the effect of changing weight for safety from 0% to 100% on the electricity mix choice. We also assume here that the remaining three criteria have the same importance for achieving a balance between the traditional 3Es for the simplification of the model, although a variety of weight combination are possible.

Table 2.3 Pairwise comparison of for criteria and their normalized weights

	Economic Growth	Energy Security	Environmental Protection	Safety	Weight
Economic Growth	1	1	1	1/3	16.7%
Energy Security	1	1	1	1/3	16.7%
Environmental Protection	1	1	1	1/3	16.7%
Safety	3	3	3	1	50.0%
			C.I. =	0.000	

(ii) Pairwise comparisons of alternative scenarios with regard to the criteria

Pairwise comparisons of the three alternatives scenarios were conducted with regard to the each of the four criteria. Table 2.4 shows the pairwise comparison given based on the data in Table 2.2. The weights show that the nuclear 20% scenario has the highest weight and the nuclear 0% has the lowest weight for these 3Es criteria. This order of importance, i.e., nuclear 20% >= nuclear 15% > nuclear 0% will not change regardless of the scale, this means the 20% nuclear scenario is always dominant in evaluating the three alternatives from the 3E perspective. Also, two different safety measurements defined as above were introduced: nuclear-free preference and fatalities-based measurement of risks on safety risks (Table 2.4). All of the consistency indices are less than 0.10, indicating that the pairwise comparisons are all consistent.

Table 2.4 Pairwise comparison of three generation mix scenarios with regard to four criteria. Pairwise comparison with regard to two opposing views on safety is performed.

Economic Growth

	(A) Nuclear 0%	(B) Nuclear 15%	(C) Nuclear 20%	Weight
(a) Nuclear 0%	1	1/3	1/3	14.3%
(b) Nuclear 15%	3	1	1	42.9%
(c) Nuclear 20%	3	1	1	42.9%
			C.I. =	0.000

Energy Security

	(A) Nuclear 0%	(B) Nuclear 15%	(C) Nuclear 20%	Weight
(a) Nuclear 0%	1	1/4	1/5	9.7%
(b) Nuclear 15%	4	1	1/2	33.3%
(c) Nuclear 20%	5	2	1	57.0%
			C.I. =	0.012

Environmental Protection

	(A) Nuclear 0%	(B) Nuclear 15%	(C) Nuclear 20%	Weight
(a) Nuclear 0%	1	1	1/3	20.0%
(b) Nuclear 15%	1	1	1/3	20.0%
(c) Nuclear 20%	3	3	1	60.0%
			C.I. =	0.000

Safety - Nuclear-free preference

	(A) Nuclear 0%	(B) Nuclear 15%	(C) Nuclear 20%	Weight
(a) Nuclear 0%	1	3	4	62.5%
(b) Nuclear 15%	1/3	1	2	23.8%
(c) Nuclear 20%	1/4	0.5	1	13.6%
			C.I. =	0.009

Safety - Fatalities-based measurement of risk

	(A) Nuclear 0%	(B) Nuclear 15%	(C) Nuclear 20%	Weight
(a) Nuclear 0%	1	0.865	0.876	29.2%
(b) Nuclear 15%	1.156	1	0.909	33.7%
(c) Nuclear 20%	1.272	1.101	1	37.1%
			C.I. =	0.000

2.2.4. Sensitivity Analysis of Safety Criteria

A sensitivity analysis was conducted to observe how the importance of the safety criterion affects the choice of the optimal generation mix. The original weight given for the safety criterion is 50% for both public views and fatalities-based measurement of safety risks, and we changed the weight for the safety criterion from 0% to 100% while keeping given proportional weights for 3Es criteria so that total weights for the four criteria sums to 100%.

2.3. Results

2.3.1. AHP Model

Figure 2.2 shows the weight distribution of each criterion among the three scenarios. In conjunction with the other three criteria, the two opposing safety views provide totally different priority rankings for these three alternatives. In the criterion layer, safety is given high preference with a weighting of 50% and each of the 3Es criteria is given 16.7% and in the alternative layer, these weights are distributed among three scenarios. Weights for the 3Es criteria are allocated in the same manner for both nuclear-free preference and fatalities based measurement of risks with 16.7%. However, if chosen based upon the nuclear-free preference, that is “less nuclear, the safer”, then, 31% out of 50% of the weight for safety is allocated to the nuclear 0% scenario and it is chosen as the best generation mix. On the other hand, with the fatalities-based measurement of risk, 18% out of 50% of the weight for safety is allocated to the nuclear 20% scenario and it is chosen as the safest based upon the existing data of fatalities. These results demonstrate that opposing views (risk perceptions) on the safety criteria result in two totally different priority rankings on the energy mix alternatives. This is an interesting result for this simple AHP model that shows even though the weight on the safety criterion is the same for both opposing views, the result is totally different when applying different measurements of the criterion. It indicates the importance of selecting appropriate measurement criteria if there are different views on the criteria and an AHP can be used to model the difference in opinions.

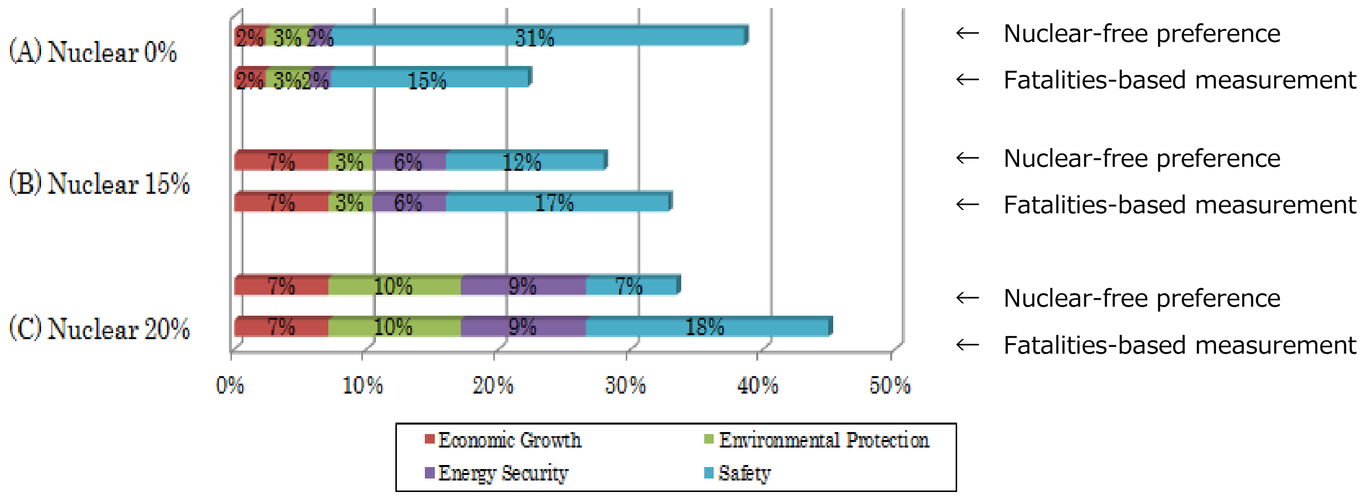
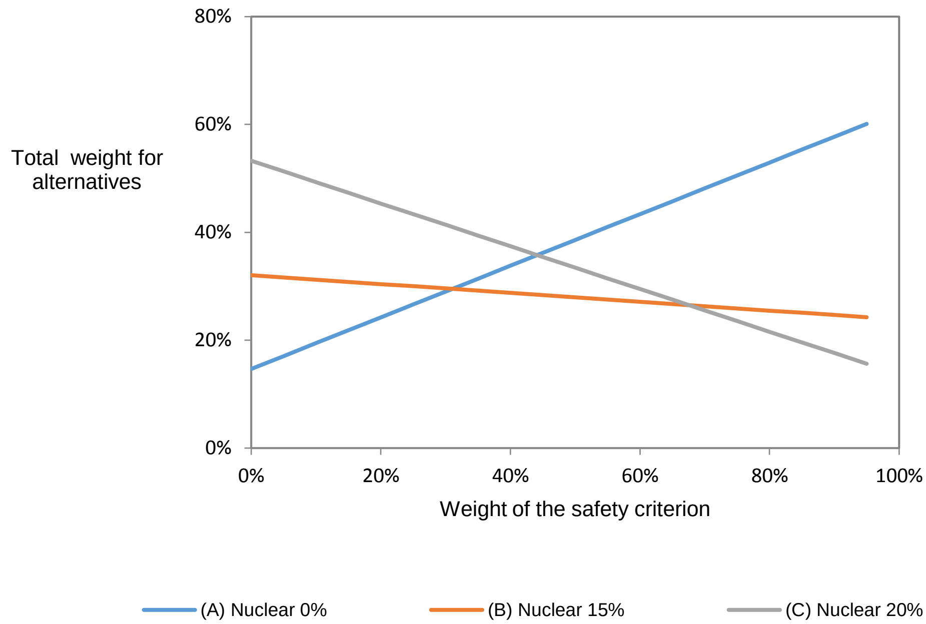


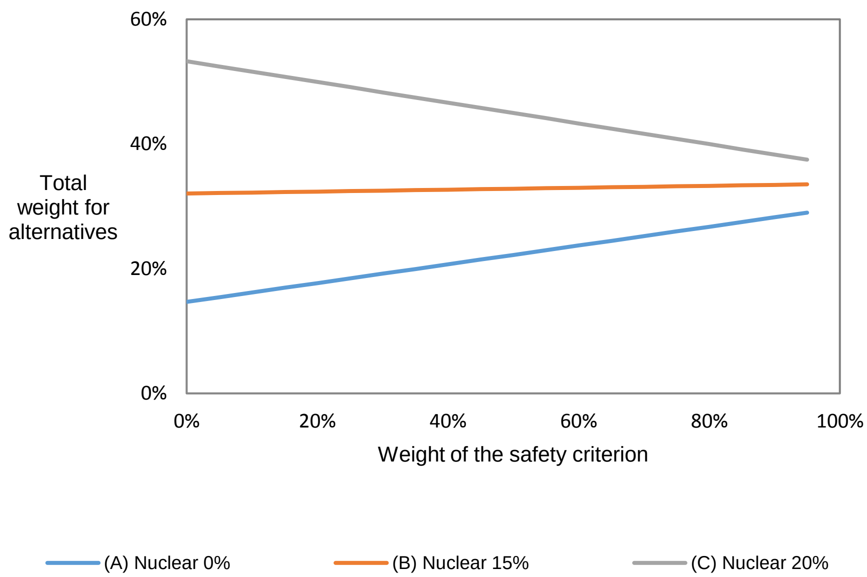
Figure 2.2 Weight distributions with opposing views on safety: Nuclear-free preference (upper) and fatalities-based measurement of risks (lower)

2.3.2. Sensitivity Analysis of Safety Criteria

In the case of changing the safety weight from 0% to 100% in both cases, sensitivity analysis of the two opposing safety criteria showed that overall, only when high preference is given to the nuclear 0% scenario with the nuclear-free preference view on safety, the model chooses the nuclear 0% scenario. First of all, with the nuclear-free preference on safety criterion, the nuclear 0% scenario is dominant when the weight for safety criterion is higher than 45%. The nuclear 20% scenario is dominant when the weight for the safety criterion is lower than 45%. Second, with the fatalities-based measurement of risks, the nuclear 20% scenario is always dominant regardless of the weight of the safety criterion (Figure 2.3). This is because the nuclear 20% scenario has the lowest measured safety risk and there is no trade-off with the 3Es' criteria. In short, unless the nuclear 0% scenario is favorably considered as the safest from the nuclear-free preference view, the nuclear 20% scenario holds a dominant position because weights by each of the 3Es criteria excels on the nuclear 20% scenario. Decision making for the optimal generation mix actually pivots on this particular viewpoint and measurement of safety criteria. The model indicates a contradictory situation that if more weight is given to the safety criterion, it becomes more difficult to reach consensus when there are two opposing measurement of safety.



(a) Nuclear-free preference



(b) Fatalities-based measurement of risk

Figure 2.3 Sensitivity analysis of two opposing views on safety: (a) Nuclear-free preference and (b) fatalities-based measurement of risks

2.4. Discussions, Policy Implications and Conclusion

The AHP model in this study clearly shows that the nuclear 20% scenario is always dominant in terms of the 3Es based upon using published data and it is also the safest option if measured statistically based upon the number of fatalities. Although this is contradictory to the public view with a nuclear-free preference, the AHP model shows that opposing views on the safety criteria leads to conflicts in decision making. The results presented here are in agreement with previous studies in terms of 3Es and from the view point of fatalities-based measurement of risks. The study by Hong et al. (2013) on the post-Fukushima generation mix scenarios with a non-AHP MCDMA concluded that a nuclear-free pathway for Japan is the worst policy option to pursue in terms of generation cost, GHG emission reduction and loss of life (safety). This is also in line with the implication of Kharecha and Hansen (2013) that showed global nuclear power has prevented an average of 1.84 million air pollution-related deaths. The AHP model introduced in this paper provides the following policy implications for the generation mix in 2030.

(1) Predominance of nuclear energy. The 20% nuclear scenario is the most appropriate in terms of the 3Es, and even safety becomes an explicit criterion for the generation mix, the 20% nuclear scenario is the safest measured based upon scientific risk using fatalities. Overall, the results imply that the nuclear 20% scenario will tend to be chosen unless the nuclear 0% scenario receives high preference based upon the nuclear-free view point of Japanese public. Therefore, it is desirable to have some share of nuclear power in the generation mix to serve the public's greater good.

(2) A need for an appropriate safety criterion. Our study showed that the choice of safety criterion will affect the overall policy preference on the generation mix

and opposing views on safety lead to conflicts in decision making. However, one of the major challenges in decision making in energy policy is to establish an appropriate definition and measurement of the level of safety comparable for all the energy resources. Even having established such a safety criterion, decision makers are still required to be prudent and able to explain in selecting an appropriate safety criterion – a fatalities-based measurement of risk may be difficult to accept for general public being skeptical on the continued use of nuclear energy, but a lower share of nuclear power may have the potential to increase the overall safety risk (fatalities) in contradiction to the Japanese's public perception. It is also worth noting that to investigate total nuclear safety including nuclear fuel cycle, not limited to the fatalities where generation takes place is challenging but necessary. Reprocessing and long-term backend fuel treatment/storage is unique to the nuclear fuel cycle and a political issue as well – only Finland and Sweden have decided on the location of geological disposal sites of radioactive waste and experience is limited in the disposal process which is expected to be carried out only after 2020 (The Federation of Electric Power Companies of Japan n.d.).

The real challenge for the policy makers is to engage the public through education and dialogue on the potential risks and the countermeasures that the nuclear power generators have to ensure that another Fukushima accident (large scale natural disaster triggers an unforeseeable man-made accident) does not occur again under the enhanced nuclear security standards.

(3) A need for multi-criteria decision-making methodology to help reach national consensus on controversial energy generation issues. There is a fundamental challenge in a democratic society to reach a consensus if there is a wide gap in opinions during decision making. Our policy recommendation is to use AHP to help decision makers to identify differences in evaluating options

and priorities among stakeholders since AHP can show a system of values and their weights in decision making. If a certain criterion is not incorporated into the AHP, the criterion is out-of-sight of decision makers. The conflict among stakeholders and opposing views on safety are inevitable in a controversial public debate on this issue. Thus, taking advantage of the model's flexibility to adapt and simplicity in structuring complex values, AHP is an effective method to analyze complex interests among stakeholders. Future work should include utilization of decision-making methods for interactive communication between the government and public. The implication of this model is that gaining support in public opinion through narrowing the knowledge based risk gap by carefully structuring the policy issue is the most important factor in the energy generation mix selection. The examination of energy mix with AHP decision making model provides a useful framework to identify the difference of opinion and how it impacts real decision making.

(4) Extension to Analytical Network Process

AHP assumes that criteria are independent. In case criteria are dependent each other, Analytical Network Process (ANP), a more generalized AHP can be applied for decision-making. In an ANP model, the criteria layer is evaluated from the scenarios in the alternative layer (outer dependence), or a criterion is affected by other criterion, such that LCOE is affected by environmental costs and safety costs (inner dependence). See, for instance, Saaty (Saaty T. , 2005) for details on ANP. In this study, authors assumed criteria are independent each other. Applying an ANP model to the same in this study is a possible future work in this field when extensive and detailed datasets explaining such a complex relationships between criteria are available.

Limitations to the scope of the study should also be mentioned. Although weights for 3Es criteria are fixed at the same proportion (the same importance in pairwise comparison) in this study for simplification, there are infinite combination of weights among these criteria. The other point is the need for the latest data. Although nuclear was dominant in terms of 3Es measured in the indices used in this study, increasing social costs of nuclear energy such as decommissioning and reduction of installation costs of renewable energy as mentioned above may lose the cost competitiveness of the nuclear energy, and thus may eventually change the comparative advantage as an energy source for electricity generation and choice in the electricity mix. Other scenarios or other electricity mix ratios could be chosen as the optimal electricity mix. A variety of scenarios such as an extreme case with more ambitious and extended use of geothermal energy that endowed richly in Japan should also be considered. Another example is the evaluation of negawatt power (Lovins, 1990), that is the theoretical unit of power representing an amount of electrical power saved and demand-side electricity saving since they have the same effect of balancing energy supply and demand as electricity generation. Nevertheless, the AHP model developed in this thesis has a generality to be used for the consideration of electricity mix not just for Japan in 2030, but also other countries, or other level of the government such as municipal government or community level. In addition, it is easy to additionally introduce criteria other than 3E + Safety, changing indices under a criteria and divide a criteria into sub criteria. For an instance of changing indices under a criteria, a municipal government would more likely to seek job creation in its administrative district in terms of economic aspect and renewable energy may be more favorably evaluated not just for environmental protection but also local job creation as well as local supply security of electricity in case of any natural disaster.

The following policy implications with regard to a broader perspective of industrial policy and maintenance of technological capabilities beyond energy policy on electricity mix should also be mentioned. First of all, each energy source requires the maintenance of technology and know-how specific to that energy. It is especially true in electricity generation from nuclear energy. Nuclear energy cannot be provided without series of technologies from material, design, operation and control, inspection of nuclear reactors that enable severe operation environment subject to irradiation under high safety standards. It will be difficult to educate future engineers and maintain employment of such engineers and operators if suspension of nuclear reactors becomes longer and new installation of reactor is not expected. Such technological capability might be eventually lost as a loss of employment. Second, as for renewable energy, installation of renewable energy has increased due to the implementation of FIT that guarantees purchase of electricity generated from renewable energy at specified prices. However, inexpensive PV panels imported from China surged about 60% in 2015 (Japan External Trade Organization (JETRO), 2015)[1] and wind turbines from European manufactures are more likely to be introduced due to their track record although their turbine technology might not be well adopted to the Japanese weather conditions such as strong wind due to frequent typhoons are different from stable westerly winds in Europe. Introduction of the FIT system in Japan has not fully resulted in developing domestic PV and wind turbine industry and its technological capabilities. Policies that encourages domestic technological capabilities are needed in order to improve competitiveness of products and adopt technologies due to weather conditions unique in Japan.

[1] In the US, the Government imposed safeguard on PV panel to China on January 22, 2018 due to economic damage caused by rapid increase of PV panel import from China (The United State Trade Representative, 2018).

The Government of Japan finally determined electricity mix for 2030 in July 2015 four years after the Fukushima Daiichi accident. It comprises the electricity mix of nuclear 20-22%, renewable energy 22-25% (PV 7%, wind 1.7%, hydro 8.8-9.2%, geothermal 1.0-1.1%, biomass 3.7-4.6%), LNG 27%, coal 26% and petroleum 3% (Agency for Natural Energy and Resources (ANRE), 2015). This is a more realistic way of setting target for future energy mix allowing some range (tolerance) in each energy source, noting that the three alternative energy mix scenarios the Japanese Government proposed in 2012 had an effect to clearly show the trade-offs in choosing scenarios with electricity prices, GHG emission and level of fossil fuel import and evoked nation-wide discussion on a future electricity mix.

Before concluding this chapter, the author attempts to interpret the Japanese government's 2030 scenario based on this study as follows. In summary, the scenario has preference on nuclear and coal, and very modest quest for renewable energy.

As the AHP model recommends the alternative (c) scenario, the electricity mix the long-term energy outlook chose has 20-22% of nuclear, the range close to the alternative (c) with the highest share of nuclear energy among three alternative scenarios. Safety is ensured by newly establishing the NRA and the world most stringent regulations for nuclear reactors, and not measured in a common metrics such as fatalities per unit electricity generation with other energy sources. The share of renewable energy at 22-24% is lower than the 30% of the alternative (c) by 6-8%. Coal is higher from the 18% of the alternative (c) by 8%, complementing the lower share of the renewable energy. The fuel costs of coal thermal power is relatively low and lower risk of supply security and coal continue to be a major energy source for electricity generation for Japan that relies most of their coal on import. On the other hand, contending large use of coal is a challenging choice for electricity generation from the environmental protection aspect as the pressure to reduce GHG emission remains high globally. It is necessary to give proper price signals to the utility and end-users by internalization of costs associated with GHG emission. Also, the report of the Cost Verification Committee clearly included the social costs associated with nuclear energy and decommissioning costs of the Fukushima Daiichi's reactors that are expected to increase. Choice for the site(s) for the final disposal of nuclear fuel are still ongoing. The uncertainty in terms of these decommissioning costs and choice of final disposal sites may have a potential to further increase the social costs with regard to nuclear energy. As a result, nuclear energy may not be cost competitive compared to other energy sources for electricity generation.

As for the cost aspect of renewable energy, it will be further cost-competitive in the future compared to other source of energy for electricity generation as decrease of equipment costs and LCOE have been observed with accelerated introduction of renewable energy. Another remarkable point of cost structure of renewable energy sources such as PV, wind, geothermal and hydro is their relatively low marginal costs compared to fossil fuel thermal power plants and nuclear energy, as those renewable energy sources do not need fuel costs. Renewable energy with low marginal costs may replace thermal and nuclear energy that have long been base load electricity sources providing low cost energy through high operational rate and low fixed costs discounted with long lifetime. The feature that marginal costs are low are especially attractive for a real-time electricity exchange market that is one of the goals of electricity market reform of the national governments. This is called "merit order system" as explained and examined further in the next chapter. In the next chapter, the authors examine the effects of introduction of renewable energy to electricity prices in the ongoing electricity market reform, extending the scope of countries from Japan to G7 countries and attempt to find commonality relationships underling the G7 countries that have both working continuously on the electricity market reform with greater introduction of renewable energies into their grids.

Chapter 3: Renewable energy's impact on international household electricity price in liberalized electricity markets: Panel data analysis on selected developed countries

3.1 Introduction

The deregulation of electricity market has been a major policy agenda item in many developed countries aiming to create a more competitive market environment that makes the electrical industry operation more efficient and thus enables it to provide electricity at economically efficient prices for end-users. The United Kingdom initiated its electricity market reform in the late 1980's and other European countries, the United States, Canada and Japan followed the UK's lead. In the 1990's, climate change has also become another major policy agenda requiring international efforts. The Kyoto Protocol in 1997 set GHGs emission reduction targets for developed countries. It also established emission trading and other economic methods that allows participating countries to implement more cost effective measures of emission reduction. It has become clear that reducing greenhouse gas emissions, inter alia, in the electricity generation and use sector, as major sources of emissions, is needed in the ongoing deregulation of the electricity market.

The effects of market reform and climate change policies on the actual electricity prices may be mixed. For example, an electricity distribution company in a deregulated market seeks inexpensive electricity from various sources. Such electricity maybe sourced from fully depreciated older facilities i.e. coal, nuclear or renewable energy such as photovoltaic (PV) and wind that have very low marginal cost in the near-term. The deregulated electricity exchange market allows an electricity company to choose the least expensive generation source in order and match electricity supply and demand in the short-term. At the same time, however, introduction of renewable energy has been financially supported by national governments through economic measures such as Feed-in-Tariff (FIT) and Renewable Portfolio Standard (RPS) to cover high installation costs and reduce investment risks. Such un-contestable costs can be transferred more easily to the household electricity prices rather than to the industrial electricity price, partially due to the national government's political and/or economic consideration for international competitiveness. Actually, the increase of electricity price has been observed in association with the increase in renewable energy in some countries despite one of the original aims of electricity market reform is to provide lower cost electricity. Pollitt (2012) pointed out that the challenge for policy makers within a deregulated market environment was that the costs of ambitious climate policy goals would be increasingly obvious to energy consumers based upon the liberalization period when placed in a wider context.

In this study, the main research questions are 1) have electricity market reforms achieved lower household electricity prices?, 2) has the introduction of renewable energy increased household electricity price in the deregulated market? and 3), how to measure or model the effect of market reforms and introduction of renewable energy on household electricity prices? To examine the above research questions, this paper is organized as follows. In the next section, the authors give an overview of the energy policy development related to electricity market reform and climate change that impacts electricity prices. Based upon prior empirical studies, both static and dynamic models are constructed to analyze the impact and significance of multiple explanatory variables such as level of electricity market regulation and percentage of renewable energy in electricity generation with regard to the household electricity price as a dependent variable. Data is prepared as internationally comparable panel data from 1991 to 2014 for seven selected OECD countries. Finally, empirical panel data analysis suggests that the household electricity prices have strong path dependency in the dynamic model and the evolution of regulatory reform on the electricity market is associated with lower household electricity price. Increasing renewable energy market penetration with lower marginal generation costs can potentially lower electricity prices in the future in a deregulated electricity market that has a spot or dynamic electricity exchange market whilst the share of renewable energy in electricity generation was not statistically significant in this study. A EU derived dummy variable was introduced to examine the homogeneity of EU member countries and heterogeneity of non-EU countries and it appears to be statistically significant.

3.2 Policy Development

3.2.1 Deregulation of electricity market

The policy objective of liberalization or deregulation of an electricity market is to create a more competitive market environment that makes electricity industry operation more efficient and thus provides electricity at economically efficient prices for end-users. Various measures have been taken in account to achieve the policy objective: reduction of government involvement in management of electric power company and price control, encouraging new entrants to enter the wholesale and retail sale markets, and unbundling of generation, transmission and distribution. Creating an EU-wide single electricity market has also been a clear policy objective of the EU (Hyland, 2016).

One of the earliest movements of electricity market reform started in the late 1980's in the United Kingdom. Thomas (2005) analyzed both forms and processes of electricity market reforms in a variety of countries and identified that a standard model for electricity liberalization is the "British model", consisting of six reforms: (1) creation of a competitive wholesale spot market for electricity, (2) creation of retail sales market where each consumer can select his provider, (3) separation of electricity distribution network activities from other market-driven activities such as generation, (4) separation of retail sales from the generation of electricity, (5) creation of an incentive structure to set market prices originally in monopolistic competition, and (6) the privatization of formerly state-owned assets. In a country's real process of deregulation of electricity market, some of these elements are integrally implemented, some of the elements are not implemented in other cases, or implemented continuously in stages in a phased or step by step manner.

The economic rational selection of energy resources in a competitive electricity market will change in accordance with the progress of market reform. But for an electricity exchange market, an electricity company has no choice but to utilize the least expensive generation source owned by the company. On the other hand in a more deregulated market with an electricity exchange market, renewable energy such as PV and wind are more likely to be used in merit order. The merit order is a way of lining up available sources of energy purely from an economical viewpoint, especially electrical generation, based on ascending order of price together with amount of energy that will be generated. That reflects the short-term marginal costs of electricity generation. In an electricity exchange market with centralized management that match grid-wide supply and demand in short-term such as 30 minutes, the order is so that the power plants with the lowest marginal costs are the first ones to be brought online to meet demand, and those with the highest marginal costs are the last to be brought on line. Dispatching generation in this way minimizes the cost of production of electricity. Implication of the merit order system to renewable energy in a liberalized electricity market is very clear. Renewable energy such as PV and wind are more likely to be brought on line first in a liberalized electricity market because of their very low marginal costs as their short-run marginal generation costs only need to cover operational and maintenance costs and without any fuel costs, hence they will become price competitive compared to fossil fuel derived electricity.

3.2.2 Economic and policy measures for climate change - FIT, RPS, ETS and Carbon tax

The FIT is a fixed price measure that government obliges electricity companies to purchase electricity generated by renewable energy such as PV, wind and biomass at a fixed price for a certain period such as ten to twenty years. The tariff is set taking into account the profit and the generation costs.

On the other hand, RPS is a quantitative measure that a government forces an electricity company to introduce certain amounts of renewable energy by themselves or purchase it from others. Theoretically, renewable energy sources are developed from the point where the costs for generation are the least expensive. So, the FIT and RPS are considered as cost efficient economic measures that allow electricity companies to introduce renewable energy in a way to lower risks associated with investment or in an order of the least expensive production of electricity and that ensures stability of the system by setting a tariff or target level. A national government plays an important role in setting an appropriate tariff and target level of renewable energy and communicating the price to electricity producers.

Emission Trading System (ETS) and carbon tax are also economic measures for environmental protection aiming directly to control greenhouse gas (GHG) emissions rather than aiming to reduce CO_2 by shifting energy mix to renewable energy. ETS sets targets and rights for GHGs emission and allows a market participant to sell/buy the extra rights and thus makes entities that set emission rights to take actions to reduce GHGs such as to implement energy saving measures, to improve energy efficiency and to shift energy mix with lower GHGs emissions. Carbon tax, also known as an environmental tax or green tax in some countries are levied based on the emission of carbon or use of fossil fuel aiming to internalize the external cost of environmental protection regarding the global warming issue.

The costs relating to FIT, RPS, ETS and carbon tax are eventually paid by the end-users added on to the electricity prices the same way as other costs for fuel, operation and maintenance, and investment by the electricity firms.

3.2.3 Progress of electricity market reform and climate change policy and measures in the selected countries

In the current study, static and dynamic panel data analysis models were developed to examine the impact of electricity market reforms and introduction of renewable energy on household electricity prices. Seven developed countries: Canada, France, Germany, Italy, Japan, the United Kingdom and the United States were selected for the panel data model because of the following reasons. First, these countries are OECD and also Group of Seven countries, accounting for one-third of world electricity consumption in total. These countries are also top-runners of world energy policy actively pursuing electricity market reform and committing to tackle climate changes, and thus give high importance to energy policy compared to other countries. Second, experiences of these selected countries have been well shared and analyzed as policy research through activities such as in OECD/IEA and in the published literature. Third, reliable, internationally comparable data are readily available for these seven countries necessary for the panel data of this study from 1991 to 2014 under common metrics without missing data. Having access to available data is very important in these practical studies.

Table 3.1 summarizes the evolution of policy measures of electricity market reform and introduction of renewable energy in the seven selected countries and EU as common energy policy base for France, Germany, Italy and UK based on the database from the International Renewable Energy Agency (IRENA) of IEA (IEA IRENA). Electricity market reforms have started in 1990's and emission reduction measures have been established in the 2000's in these countries.

Table 3.1 Summary of electricity market deregulation and renewable energy policy of the seven selected countries for the panel data model and EU

	Up to 1990's	2000's	2010's
EU	● 1996 Council Directive (96/92/EC) concerning common rules for the internal market in electricity	● 2001 Council Directive (2001/77/EC) concerning renewable energy electricity promotion ● 2003 Council Directive (2003/87/EC) establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC ● 2003 Council Directive (2003/96/EC) for energy tax ● 2003 Council Directive (03/54/EC) concerning Common Rules for the Internal Market in the Council Directive (96/92/EC) ● 2005 EU Emission Trading System started ● 2007 European Council Action Plan for Energy Policy	● 2003 Council Directive (03/54/EC) for cross-border exchange in electricity and the electricity markets will be fully open to competition by 2005 (2007 for household customers). ● 2009 Council Directive (2009/28/EC) for renewable energy 20% target by 2020 and abolished related Council Directives (2001/77/EC and 2003/30/EC) ● 2009 Council Directive (09/72/EC) concerning Common Rules for the Internal Market in Electricity and repealing the Council Directive (03/54/EC)
France	● Government owned electricity company EDF incorporated	● 2000 Introduction of FEI by Electricity Law 2000 ● 2005 Energy law of 2005 ● 2007 Electricity market fully liberalized ● 2009 Grenelle I ● 2010 Grenelle II	● 2015 Household electricity price regulation abolished ● 2015 Energy Transition for Green Growth Act
Germany	● 1991 Electricity Feed-in Law ● 1998 Electricity market fully liberalized	● 2000 Renewable Energy Source Act (FIT)	● 2014FIP
Italy	● 1992 Government owned electricity company ENL incorporated ● 1992 FIT ● 1999 Open market for consumers with	● 2000 open market for consumers with +20GWh ● 2002 +9GWh ● 2003 +0.1GWh ● 2007 Electricity market fully liberalized ● 2002 RPS	● 2012 FIP

	30GWh/year (market openness at 30%)		
United Kingdom	• 1990 Electricity Act (Privatization of national electricity company)	• 2000 Utilities Act • 2002 Introduction of Renewable Obligation • 2004 Energy Act(Single wholesale market)	• 2010 FIT • 2012 Abolishment of Renewable Obligation • 2014 CfD
United States	• 1978 Public Utilities Regulatory Policy Act (PURPA) for independent power production • 1992 Energy Policy Act of 1992 - efficiency • 1996 FERC Orders 888 and 889 required electricity firms unbundling of generation and transmission sector and third-party use of the grid system. Establishment of Independent System Operator (ISO) • 1999 FERC Order 2000 - Regional Transmission Operator (TSO) • State activity related to retail choice began in the mid-1990s. Competitive retail sales introduced in a selected number of states.	• 2005 Energy Policy Act of 2005 – comprehensive energy policy including energy efficiency improvement, incentive to the introduction of renewable energy and nondiscriminatory access to grid	
Canada		• 2009 State of Ontario first introduced FIT in North America	
Japan	• 1995 Power Producer and Supplier • 1999 Independent Power Producer	• 2000 Retail sales (2000kW+) • 2003 Japan Electric Power Exchange established • 2004 Retail sales (500kW+) • 2005 Retail sales (50kW+) • 2003 RPS FIT(PV only)	• 2016 Retail sales (household) fully liberalized • 2012 FIT

Note: Feed- in Premium (FIP), Contract for Difference (CfD), Federal Energy Regulatory Commission (FERC)

3.2.4 Changes in electricity prices

Figure 3.1 illustrates the historical trend in the ratio of the unit household electricity price to the unit industry electricity price in the seven selected countries for the panel data model. The household electricity price is generally higher than the industry electricity price and Figure 3.1 shows that the ratio is higher than 1 for all except for Italy after 2011. This is because electricity price for industry is contracted with large volume industrial users and thus the unit price is set relatively low. Industrial electricity price is also set lower, because of deduction or reduction of carbon tax due as economic policy to maintain international competitiveness of a country's industry and to prevent energy intensive domestic industries' transfer of production overseas. On the other hand, household electricity price is reduced in some countries based upon social welfare concerns for households with lower income or living on pension (Tsutsui, 2012). The observed discontinuous change in France in 2007 in the Figure 3.1 is due to the liberalization of household electricity as noted in the above section.

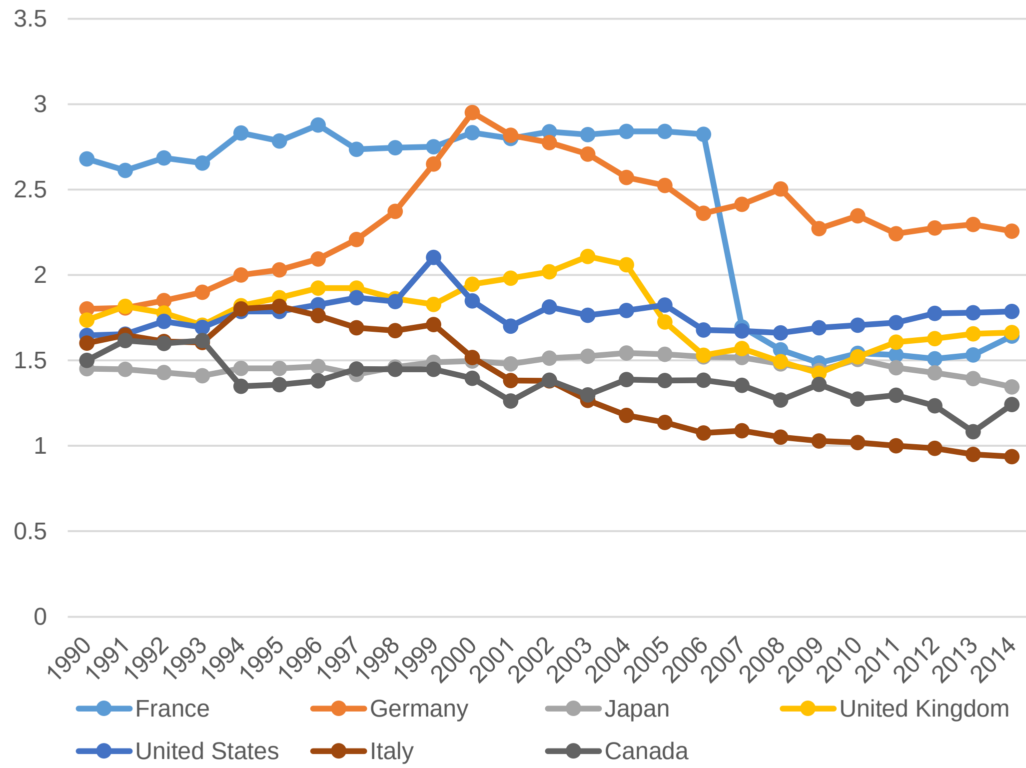


Figure 3.1 Ratio of household electricity prices to industrial electricity prices in years 1990 - 2014 of the seven selected countries for the panel data model

Source: IEA Energy Prices and Taxes (2015)

3.3 Prior empirical studies

There are many prior works analyzing the relationship between electricity prices and introduction of renewable energy. Impacts of market reforms of electricity industry to the electricity prices were analyzed by computable general equilibrium model showing that a competitive market environment decreases electricity price (Akkemik & Oğuz, 2011), (Kunneke & Voogt, 1997). Steiner (2000) concluded that regulatory reforms brought competition into the market and generally decreases industry's electricity prices, and widens the gap between industry and household electricity prices by using the data from 1986 to 1996 for 19 OECD member countries. As a comparison to the Steiner's study, Hattori and Tsutsui (2004) conducted a panel data analysis for 19 OECD member countries from 1987 to 1999. They found that expanded retail access, i.e., giving customers access to alternative suppliers is likely to lower industrial electricity prices and widening price gap between industry and household electricity prices. They also showed that unbundling in the generation sector and introduction of spot market in the wholesale electricity market can bring higher industrial electricity prices.

Nagayama (2009) analyzed 78 countries covering developed countries, developing countries and economies in transition from 1985 to 2003. He concluded that electricity market reforms did not necessarily bring a decrease of electricity prices but rather the prices tended to rise in contradiction to one's expectation. He pointed out the endogeneity of electricity prices that the electricity prices were affected by the market reforms and vice versa, also an increase of electricity prices could curtail poor households' access to the electricity in developing countries, and decrease of electricity prices could discourage the effort of energy saving and have a negative impact on the recovery of investment. To avoid endogeneity, he introduced an ordered response, probit model with lagged terms in his first model to observe the impact of electric power prices on the selection of a liberalization model in the power sector. To address the simultaneity bias issue in his second model that aimed to estimate the impact of the liberalization model on the electric power price, he introduced the instrumental variable (IV) method in the third model. Note that examination of the effect of introduction of renewable energy on electricity prices was not the main focus of the study.

Jamasb et.al (2004) concluded that based on the analysis of the econometric evidence in prior studies, privatization of government-owned electricity company does not impact electricity prices and introduction of competition has both positive and negative aspects. Jamasb's work summarizes prior studies published mainly up to the first half of the 2000 decade. They referred to the ACER 2014 annual internal electricity market monitoring report that shows a general increasing trend in household electricity prices due to the non-contestable charges largely due to the contributing growth in renewable deployment incentives.

Moreno et al. (2012) introduced a static panel data analysis to evaluate the impact on household electricity prices by the introduction of renewable energy and electricity market reform in 27 European Union countries from 1998 to 2009. They suggested that electricity prices increase with the deployment of electricity generation from renewable and with the expansion of GHGs emissions by energy industries - as the EU CO_2 emission trading scheme exists. Their results also revealed that country's characteristics could affect household electricity prices.

Hyland (2016) studied the effect of EU electricity market reform process to the industry electricity prices using data covering 28 European countries (27 EU countries before Croatia joined the EU and Norway) from 2001 to 2011. She pointed out the necessity of taking into account the endogeneity of the market reform process, i.e., the reforms influence the electricity prices and the electricity prices also influence the reforms (simultaneity). She conducted two types of panel data analysis on a fixed effects model (static model) assuming that variables were exogenous and a dynamic model constructed taking into account the endogeneity. A two-step Generalized Method of Moments (GMM) was adopted in the dynamic model that is robust with regard to autocorrelation and heteroscedasticity in panel data. She also used the Windmeijer finite-sample correction of the variance for the more accurate inference since the use of two-step estimator can cause severe downward bias in the standard errors in small samples (Windmeijer, 2005). She showed that although the liberalization of the wholesale electricity market is associated with the lower industrial electricity price in the static model, the electricity price in Europe has a strong path dependency thus the analysis should not be done using a static framework. In the dynamic model, she also showed that unbundling of transmission system operator does not affect the industrial electricity prices both notwithstanding the model is exogenous or endogenous. She concluded that the electricity market reform has not had a statistically significant impact on the industrial electricity prices so far in the dynamic panel data model. The impact of renewable energy on the industry electricity prices is not the primary focus of her study but it certainly was examined in the model using explanatory variables of 1) share of hydro and nuclear power as a country's generation mix that is also likely to have an important impact on electricity prices, and 2) existence of renewable support schemes in a country by using IEA/IRENA Joint Policy and Measures Database as a dummy variable. She found that the share of hydro plus nuclear power has basically negative impacts and is statistically significant under some conditions. The existence of a renewable support scheme has a strong positive impact and is statistically significant under some conditions on the industrial electricity prices.

Da Silva and Cerqueira (2017)'s research purpose was to assess the main drivers of household electricity prices and they constructed a dynamic panel data model. With the data across 23 out of 27 EU member countries from 2000 to 2014, they concluded that liberalization is accompanied by a decreasing trend in prices and date of market liberalization has a significant negative impact on prices. As for the impacts of renewable energy on household electricity prices, they found that electricity production from renewable sources as share of the overall gross electricity consumption is always positively correlated and significant under all conditions and GHGs per capita is positive but not significant in their EU wide model. Methodologically, their GMM used a two-step approach by Blundell and Bond (Blundell & Bond, 1998) with the Windmeijer correction (Windmeijer, 2005).

In this study, the authors conducted a novel panel data analysis covering seven selected OECD countries from 1991 to 2014 to evaluate both the impact of electricity market reforms and introduction of renewable energy on household electricity prices based on the prior empirical studies utilizing the static panel data analysis by Moreno et al. and dynamic panel data analysis by Hyland, da Silva and Cerqueira. We also assume endogeneity of electricity prices arise from simultaneity and omitted variables, such that the electricity prices were affected by the market reforms and introduction of renewable energy, and electricity prices also affect progress of market reforms and introduction of renewable energy. Electricity prices are also affected possibly by other elements like GDP and electricity consumption, international oil price, energy dependency that are explicitly included in the model but also other elements included as in the error term. The author's approach to address endogeneity is to use GMM as a dynamic model, compared with the static model where explanatory variables are assumed to be exogenous. GMM is a very general method of dynamic panel data estimation that encompasses the ordinary least squares (OLS), generalized least squares (GLS) and method of instrumental variable method (IV) as its special conditions, being able to deal with endogenous variables, lagged terms of dependent variable can be used as instrumental variables that enables to handle both endogeneity and autocorrelations. The author introduced a lagged dependent variable to explain the persistence of the price series after examining results of the model.

The differences from the prior works are as follows. In our models, the data coverage is the longest e.g., covering 24 years starting from 1991 to including the latest data in 2014 to covering deregulation activity. In the static model, splitting this 24 year period into two periods, the data for the first half from

1991 to 2000 and the second half from 2001 to 2014 are compared in order to examine the effect of introduction of renewable energy because many developed countries started to take concrete measures to reduce GHG emissions such as by FIT and RPS in 2000's.

More in detail, endogeneity is taken into account in the dynamic model using lagged household electricity prices as a dependent variable, and the time series is not split into two separate terms. To examine impacts of electricity market reforms and introduction of renewable energy on the household electricity prices not only limited to EU wide, the country coverage consists of not only the EU member countries of France, Germany, Italy and the UK which have EU wide common energy policy directions on electricity market reform and climate change, but also three countries from outside the EU (Canada, Japan and the United States). A dummy variable for the EU member countries are introduced in order to handle homogeneity of EU member countries and heterogeneity of the non-EU countries. Also, in order to take into account the multi-faceted and phased nature of electricity market reforms, OECD's regulatory index is adopted as an explanatory variable. This index can measure a country's level of electricity market reform by weighting and integrating various aspects of electricity market reforms about entry regulation, public ownership, vertical integration and market structure. In the dynamic model, the authors use a two-step GMM where the first lag of the level of the household electricity price is used as an explanatory variable.

3.4 Model for Panel data analysis

This section describes the model and results obtained. The first subsection describes the data used and the second subsection shows the model specification and finally the estimation results.

3.4.1 Data

The data of the seven selected countries presented in this analysis was obtained from the database published by international organizations such as IEA and World Bank that have historically been accumulating and publishing these reliable time series data.

All the data for variables are obtained for the seven OECD countries from 1991 to 2014. The dependent variable is the household electricity price (P) measured in US cent/kWh and deflated to the 2014 year price level. The seven explanatory variables are carefully selected from four groups that represent different aspects of energy policy objectives; electricity market reform, environmental protection, energy security and economic development as follows.

3.4.1.1. Level of electricity market reform: Regulatory index by OECD

One of the outstanding features of the data analyzed in this study is the use of OECD regulatory index, which is very useful in international comparison and illustrates multi-facet nature of electricity market reform such as price regulation, unbundling of generation-transmission-distribution, third party access to the electricity grid and privatization of national electricity company. For instance, a share of entrants in all utilities operators measured in the number of users or amount of electricity consumption is an index to measure openness of the wholesale or retail sales market. A government's percentage of share is considered as the control on the regulated utility operators. Level of unbundling varies from independent accounting in a vertically integrated utility operator to a split-up of an independent generation, transmission and distribution company. The Herfindahl-Hirschman Index is defined as the sum of the square of share in a market of all of the companies participating in the market and sometimes used to illustrate the level of concentration of the market.

However, it is very challenging to use such indices in an international panel data analysis that seeks to grasp the multi-facet nature of market reform and different stages and measures undertaken by governments. Furthermore, obtaining time series data is sometimes difficult where the definition and data metrics are different in each country. On the other hand, the following OECD regulatory index (RI) is very useful in the panel data analysis like in this study because the index has a structure that integrates the multiple aspects of electricity market reform over the time period of interest.

OECD (2015) started developing indicators of product market regulations called the Indicators of Regulation in Energy, Transport and Communications (ETCR) in 1998 and updated the data in 2003, 2008 and 2013, when the latest update coincided with the improvement of the methodology. The data covers 34 OECD member countries and 21 non-member countries from 1975 to 2013. The authors adopted the RI on the electricity industry covering seven network market regulation indexes (telecoms, electricity, gas, post, rail, air passenger transport and road) in this panel study. This electricity market RI consists of four sub-indexes of Entry Regulation, Public Ownership, Vertical Integration, and Market Structure and each has a quarter of the total weight. Each of these four sub-indexes consists of further sub-indexes. For instance, the Entry Regulation consists of three sub-indices with one-third of the weight such that 1) how are terms and conditions of third party access to the electricity transmission grid are determined, 2) is there a liberalized wholesale electricity market and 3) what is the minimum consumption threshold that consumers must exceed in order to be able to choose their electricity supplier. The RI is defined to take the value from 0 (most liberalized) to 6 (most regulated). Details are provided in Koske (2015). Taking advantage of the integrated nature of the ETCR index, Fiorio and Florio (2013) used the ETCR data in their study on the impacts of different aspects of corporate ownership on residential electricity prices. Note that some missing values in the OECD's original RI data for the purpose of this panel data analysis were estimated and interpolated.[2]

3.4.1.2. Environmental Protection indexes: Renewable energy and CO_2 emission

The share of renewable energy in electricity generation (REEG) and CO_2 emission per capita are adopted to measure the progress of policy to tackle climate change. The level of renewable energy is dependent on the initial endowment of economically and technically exploitable renewable energy and the national governments' intention and actual measures of energy policy for introduction of renewable energy. The CO_2 per capita is measured excluding the CO_2 emission through cement production process that is less relevant to the electricity use. These two indicators are selected aiming to illustrate two environmental aspects of energy mix that are exclusive to each other. CO_2 emission represents fossil fuel use in the energy mix such as coal, petroleum and natural gas, and renewable energy consists of hydro, wind, photovoltaic,

[2] The data for US from 1998 to 2013 are estimated by linear interpolation using published data of four time points of 1998, 2003, 2008 and 2013. For the data from 1991 to 1997 where linear interpolation is not available, the data for 1998 is extrapolated. For the data of 2014 of all seven countries, the data for 2013 is used assuming no change in regulation that affects the index. The authors concluded that this is on safety side, reasonable treatment of missing data after careful consideration of the following alternative methods and feature of the data.

First of all, theoretically, there are a number of ways to automatically impute missing data when unbalanced data is used in economic models, such as simply replacing a missing value with the average of the series, with the average of the values neighboring to the missing value, with the median of the values neighboring to the missing value, linear interpolation, or extend the trend of the neighboring values. It is also possible to use multiple imputation method such as full information maximum likelihood method, autoregressive model and moving average model for rigorous interpolation/extrapolation.

However, looking at the real RI data, they are mostly inactive in a time span of several years. Canada has 3.38 for all years after 2005, France has the same value 3.19 for 2011-2013 and 3.57 for four years in 2007-2010, Germany has 1.17 for all years after 2005, Italy has 2.15 for 2013 but 2.16 for 2010-2012, Japan has the same value 2.15 for 2012-2013 and 1,40 from nine years in 2003-2011, UK has 1.17 for all years after 2002. Also the RI has usually gone down (deregulation) and rarely gone up (re-regulation). RI of each country should be independent, as it reflects level of national regulation implemented by each sovereign country and are assumed not affected by other countries. For EU countries, they have accorded energy and environmental policy to some extent, but timing of introduction of new policy measures and its intensity are different based on the country's own policy.

biomass, geothermal and so on. CO_2 emission could affect the electricity prices through carbon tax and emission trading system that internalize the costs associated with the environmental protection by GHG emissions. On the other hand, renewable energy could affect the electricity prices through FIT and RPS that forces electricity industry to acquire renewable energy at a fixed price level or specified quantity.

3.4.1.3. Energy Security Index: Energy dependence

There are various indexes to measure the situation of energy security such as energy self-sufficiency rate, level of distribution of fossil fuel energy import countries, share of energy imported through geographical choke points in total imported energy. In prior studies, APERC proposed four aspects in examining energy security; energy resource availability, accessibility barriers, environmental acceptability and investment cost affordability (Asia Pacific Energy Research Centre, 2007). In this study, energy dependency (ED), defined as the percentage of net energy import in the energy use, is adopted from the viewpoint of the data availability and measurement in common metrics for international comparison. The ED data takes both positive and negative values by definition. The UK and Canada are net energy exporting countries (UK only for 1991-2004) and thus the index takes a negative value. Other countries are net importers of energy resources and have positive values. Japan has the highest positive value at 94% in 2014 due to the shutdown of its nuclear power plants for legal inspection and consequent suspension after the 3.11 earthquake in 2011 among these seven selected countries.

3.4.1.4. Economic Development index: GDP per capita, International oil price and Electricity Consumption per capita

As economic development index, three indicators are examined; GDP per capita, international energy price and electricity consumption per capita. GDP is a major index generally used in measuring the level of economic development. The data were deflated using US$ for the year 2014. As for the international energy price that aims to approximate the variable costs input for generation, prices of US imported petroleum was used. The international oil price (IOP) fluctuates significantly over the period analyzed from the lowest price of US$ 13 per barrel in 1998 to the highest price at US$ 105 per barrel in 2012. Electricity consumption per capita (EC) is also selected to represent the electricity demand assumed to increase along with economic development. IOP is considered as a time specific variable in this model as that are internationally traded oil prices and common to each countries.

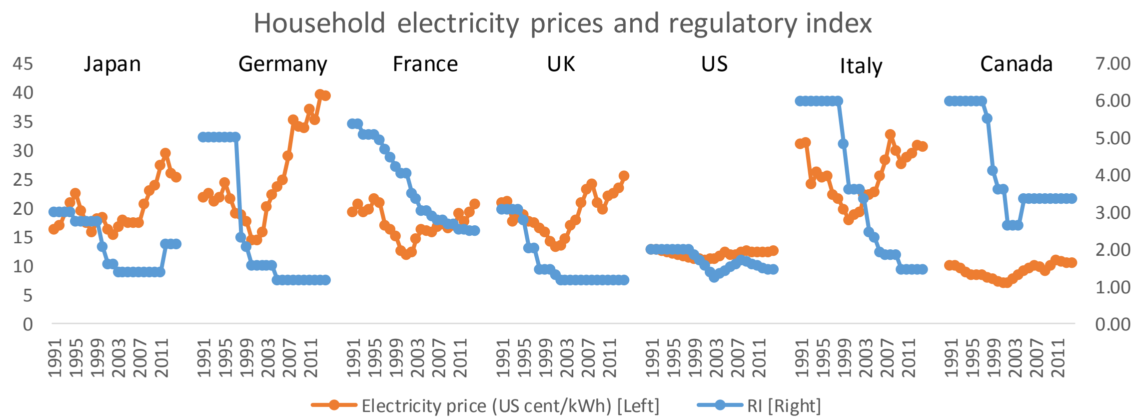
A EU dummy variable (1 for EU member countries: France, Germany Italy and the United Kingdom, and 0 for non-EU countries: Canada, Japan and the United States) is also introduced to examine the homogeneity of EU member countries and heterogeneity of non-EU countries in energy and environmental policy.

Table 3.2 summarizes the descriptive statistics of these variables with their data sources. It shows significant variation of the data due both to the difference of situation in each country and time series development of these variables such as RI and GDP.

Table 3.2 Descriptive statistics of the variables

	Mean	SD	Min	Max	Source
Household electricity price [US Cent/kWh]	18.3	7.1	7.1	39.5	IEA (2015)
France	17.3	2.7	11.9	21.6	
Germany	25.3	8.0	14.3	39.5	
Italy	25.6	4.5	17.8	32.7	
UK	19.1	3.4	13.3	25.6	
Canada	9.1	1.2	7.1	11.0	
Japan	20.0	4.0	15.4	29.4	
US	12.0	0.5	11.0	12.8	
Regulatory Index	2.8	1.5	1.2	6.0	OECD/ETCR (n.d.)
France	3.7	1.1	2.5	2.5	
Germany	2.5	1.7	1.2	5.0	
Italy	3.6	1.9	1.4	6.0	
UK	1.7	0.7	1.2	3.1	
Canada	4.2	1.3	2.6	6.0	
Japan	2.1	0.7	1.4	3.0	
US	1.7	0.3	1.3	2.0	
Renewable energy in electricity generation [%]	20.0	18.6	1.8	64.8	USEIA (2017)
France	14.2	2.0	10.6	18.1	
Germany	12.1	7.6	4.1	28.7	
Italy	23.3	7.4	16.8	45.7	
UK	5.8	5.0	1.8	21.2	
Canada	62.3	1.6	59.2	64.8	
Japan	11.2	1.3	8.8	15.2	
US	10.8	1.5	8.0	13.7	
CO_2 emission per capita [10^3 metric tons of carbon]	2.9	1.2	1.3	5.4	US DOE (n.d.)
France	1.6	0.1	1.3	1.8	
Germany	2.7	0.2	2.4	3.1	
Italy	1.9	0.2	1.4	2.1	
UK	2.3	0.2	1.8	2.7	
Canada	4.4	0.2	4.0	4.7	
Japan	2.5	0.1	2.3	2.7	
US	5.0	0.3	4.3	5.4	
Energy dependence [%]	34.7	46.2	-77.6	94.0	World Bank (n.d.)
France	47.9	1.6	43.6	49.9	
Germany	58.8	2.8	51.1	62.1	
Italy	82.2	2.7	75.4	85.4	
UK	2.4	22.5	-26.8	42.3	
Canada	-53.1	9.1	-77.6	-37.0	
Japan	82.7	4.8	78.2	94.0	
US	21.9	5.3	10.3	29.7	
GDP per capita [US$]	33,796	9,548	18,389	54,540	World Bank (n.d.) and IMF (n.d.)
France	31,820	8,594	21,782	45,413	
Germany	33,690	8,482	23,269	47,903	
Italy	28,092	7,459	18,677	40,640	
UK	33,179	9,890	18,389	49,949	
Canada	32,667	12,565	19,859	52,495	
Japan	37,680	4,994	28,541	48,629	
US	39,446	9,545	24,405	54,540	
International oil price [US$/barrel]	47	34	13	105	IMF (n.d.)
Electricity consumption per capita [kWh]	8,907	3,899	4,225	17,235	
France	7,156	426	6,360	7,735	
Germany	6,823	370	6,245	7,281	
Italy	5,167	522	4,225	5,833	
UK	5,793	336	5,130	6,271	
Canada	16,336	585	15,270	17,235	
Japan	8,009	467	7,009	8,710	
US	13,062	486	12,015	13,705	World Bank (n.d.)

Figure 3.2 shows the household electricity prices vs. the regulatory index (above) and household electricity prices vs. percentage of renewable energy in the electricity generation (below) for the seven countries. It illustrates the progress in the market reforms (downward trend in the level of regulatory index) does not seem to coincide with the decrease of household electricity prices at least in the latter half of the period. Rather than that, an opposite trend is observed clearly in Germany, the UK and Italy. As for the relation with renewable energy, it also illustrates that increase of the household electricity prices seems to coincide with the increase of share of renewable energy in electricity generation especially in France, Germany, the UK and Italy.



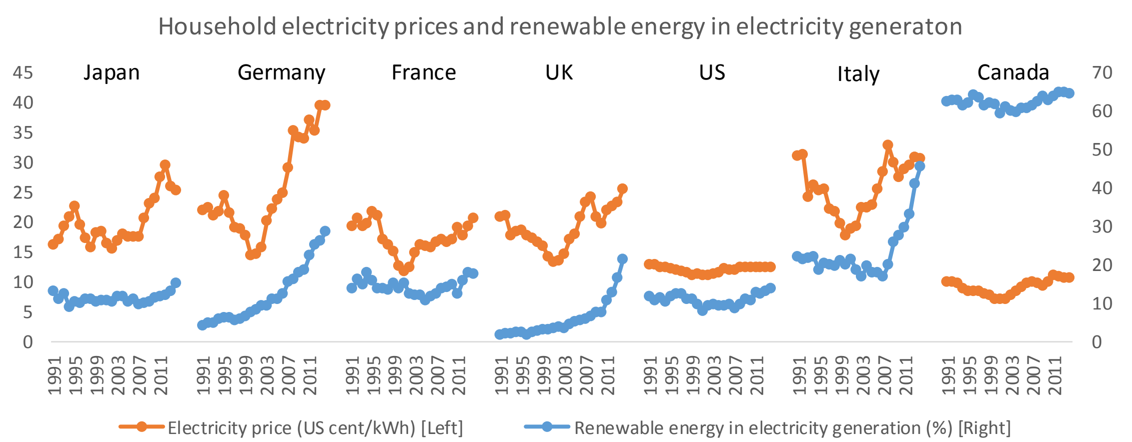


Figure 3.2 Relation between household electricity prices with regulatory index (above) and with percentage of renewable energy in electricity generation (below) of the seven selected countries for the panel data model

3.4.2 Estimation model and results

In this study, the authors constructed static models with two different periods and one dynamic model with a lagged level of the dependent variable. As noted in the empirical study in the Section 3.3, da Silva and Cerqueira justified the use of GMM on the basis that traditional fixed effects estimator is biased in the presence of the lagged dependent variable as regressor and it also accounts for possible endogeneity of some of the dependent variables (Da Silva &

Cerqueira, 2017). In the current study, using the same data set both for the static model and the dynamic model can show differences in the estimators.

In the static model, the authors expected the following relationship between the independent variable and explanatory variables. Figure 3.3 illustrates the conceptual model that explains the relationship the authors expect among seven explanatory variables and the dependent variable.

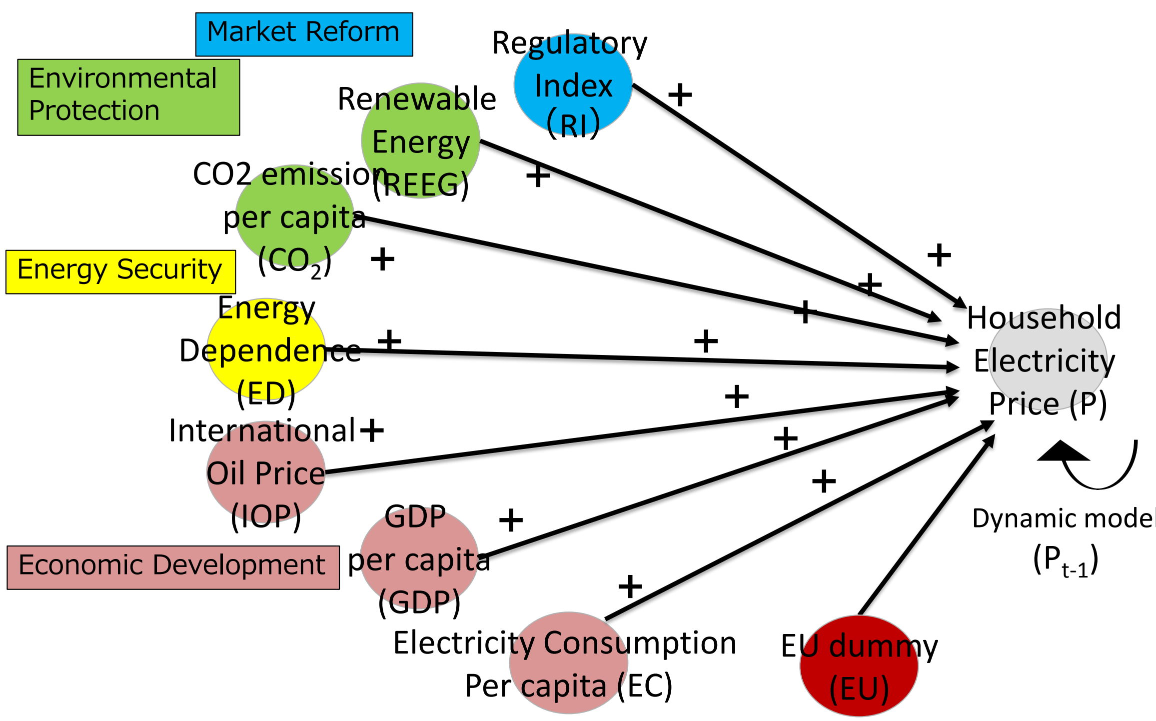


Figure 3.3 Theoretical model of the parameters and interaction on the household electric prices

- Expectation 1: A positive correlation between the progress of market reform (lower regulatory index) and lower household electricity prices, as the market reform is aiming to provide efficient and a competitive environment for the electricity industry. The authors also expect that the elasticity of household electricity prices to the RI is higher in Period I and becomes lower in Period II because the effect of lowering prices by market reform would be cancelled by the effect of increasing electricity prices by higher introduction of renewable energy.

- Expectation 2: A positive correlation between the higher level of renewable energy in electricity generation and higher household electricity prices. Also, a higher CO_2 emission level coincides with higher household electricity prices. The assumption behind this is that costs associated with the introduction of renewable energy such as FIT, RPS, and GHGs emission reduction costs are internalized by the ETS and carbon tax, which are passed on in higher electricity prices. In addition to that, the elasticity prices would be higher in the Period II due to the progress of introduction of renewable energy and CO_2 emission reduction measures.
- Expectation 3: The authors expect a positive correlation between higher energy dependence and higher electricity prices. The importation of tradable natural resources such as coal, petroleum and natural gas to a country is justified when such energy resources are not produced domestically or available at the price lower than their domestically produced costs. However, it is also natural to think that a country with higher energy dependence is more susceptible to risks associated with internationally energy disturbances – price fluctuations and any kind of supply shock, and such a country would be more eager to improve their energy security situation by introducing more domestically produced energy such as renewable energy even if it is less cost effective, or improving efficiency in energy use.[3] Thus, the authors expect higher household electricity prices coincide with the higher energy dependency.
- Expectation 4: A positive correlation between higher economic development, i.e., higher GDP per capita, higher IOP and higher EC and higher household

[3] Nuclear energy is defined as a quasi-domestic energy resource by IEA/OECD due to the long-term storability and recyclability of the fuel.

electricity prices.

3.4.2.1 Static model

With regard to the first and the last expectation, however, the authors also anticipate the endogeneity in the share of renewable energy and economic development indicators against the household electricity prices. The status or progress of the market reform will affect the electricity prices and the progress of the market reform is also affected by the prices. Higher electricity prices could reduce electricity consumption (less EC) and hinder the economic growth (less GDP) and such a change in the electricity demand will again impact the household electricity prices. This endogeneity aspect is analyzed later in the dynamic model.

In order to identify and compare the impact of electricity market reform, introduction of renewable energy and other elements that might affect household electricity price, the following panel regression model is defined for the static model as in equation (1) based upon the above expectations.

$$Ln(P_{it}) = \alpha_i + \beta_1 RI_{it} + \beta_2 REEG_{it} + \beta_3 \ln(CO_{2it}) + \beta_4 ED_{it} + \beta_5 \ln(GDP_{it}) + \beta_6 \ln(IOP_t) + \beta_7 \ln(EC_{it}) + \beta_8 EU_i + \mu_i + \varepsilon_{it} \quad \cdots (1)$$

Where i = 1, … , 7 (Canada, France, Germany, Italy, Japan UK, and US), t = 1991, …, 2014 and α_i parameter denotes country effects to take into account for any country-specific factors that may influence and do not change household electricity prices over time. The β are partial correlation coefficients. The disturbance terms μ_i is assumed to be specific to an individual country and does not change over time. The ε_{it} is an idiosyncratic error term, assumed to be independent from the regressor and individual error component μ_i, and has the standard properties of $\varepsilon_{it} \sim N(0, \sigma_\varepsilon^2)$.

The authors also examine a revised static model limiting the explanatory variables other than the EU dummy from seven to four excluding CO_2, IOP and EC to avoid multicollinearity.

In the formulation of the models, the variables in the analysis are expressed in the log form unless the original data is expressed as a percentage or numerical index. Therefore, each partial correlation coefficient in the regression model means point elasticity of the dependent variable to the corresponding explanatory variable in case of log forms.[4]

A random effects model is used in the following section in the static model because the EU dummy is a time-invariant explanatory variable, which is omitted since it does not yield coefficients in the fixed effects model[5].

3.4.2.2 Dynamic model

As Hyland (2016) pointed out that the major shortcoming in much of the analyses on the impact of market reform is a failure to take into account the potential endogeneity of the reform process. For example, the basic (static) panel regression, causality may run in both directions that prices may be influenced by the market reform process and likewise they may also be an important driver in the decision to reform the market, and thus the explanatory variables may be correlated with the disturbance term. In her study, a lagged dependent variable was introduced in the model as autoregressive properties of the dependent variable. Her finding was that the lagged dependent variable was significant.

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[4] In the case where both dependent and explanatory variables are in log forms, the partial correlation coefficients represent elasticity (percentage change of dependent variable to the percentage change in the corresponding explanatory variable). In the case where only explanatory variables are in the log form, the partial correlation coefficients represent a dependent variable's rate of change to the unit change of the corresponding explanatory variable.

[5] Stata software student version was used in modeling the data. Commands for random effects model are: xtreg in generalized least squares estimation and xthtaylor in Hausman-Taylor estimation, The Hausman-Taylor estimation assumes endogenous variable in its regression model, See Hausman & Taylor (1981) for details.

The reasons for the importance of examining a dynamic model in this research are as follows. First, the autocorrelation nature of the electricity prices. It is intuitively reasonable to assume path dependency that the current level of household electricity prices are more related to the level of the previous time period to some extent and not determined in an entirely stochastic manner. Furthermore, the current price level is more associated with the latest price level than with previous time frames. Second, to capture the endogeneity, defined as the correlation between the explanatory variable(s) and error term in econometrics, arising from omitted variables, measurement error and simultaneity. The simultaneity of dependent and independent variables such that GDP and introduction of renewable energy influence electricity prices and vice versa can be easily assumed in the real world economic activity.

A GMM model can handle the autocorrelation of the dependent variable by introducing lagged variable as an explanatory variable and introducing instrumental variables that are orthogonal to the error term to estimate endogenous variables by setting moment conditions.

In the dynamic model of the current study, the following model with a lagged term of household electricity price P_{it-1} as the explanatory variable and a dynamic GMM estimator is defined and used as shown in Eqn. (2). The authors carefully selected only the GDP in the economic development indicator group and excluded the IOP and EC after checking their high correlation with GDP and model suitability in order to avoid multicollinearity. ED is also excluded after examining combinations of explanatory variables so that the model yields a result with a good p-values for the coefficients, Sargan test, autocorrelation test and Wald test. The time-invariant EU dummy is included in order to examine the homogeneity of EU member countries and heterogeneity from the non-EU countries[6].

[6] The xtpdpd command in Stata software was used as it can accommodates the evaluation of the time-invariant

$$Ln(P_{it}) = \alpha_i + \beta_1 ln(P_{it-1}) + \beta_2 RI_{it} + \beta_3 REEG_{it} + \beta_4 ED_{it} + \beta_5 ln(GDP_{it}) + \beta_6 EU_i + \mu_i + \varepsilon_{it} \quad \cdots (2)$$

The overall period is not split into two periods in the dynamic model because including the lag term and the EU dummy limits the available data for calculation and the model is likely to be biased. The authors estimate the following three sub-categories with different combinations of instrumental variables (IV) for the level equation, in order to explore the best estimation in terms of coefficients (p-value) and of Wald test, Sargan test and autocorrelation test;

1) RI and ED
2) RI, GDP and ED
3) RI, REEG and ED.

The p-values are calculated for standard error without Windmeijer correction (SE) and standard error with Windmeijer correction (WCSE). Coefficients are the same for the same combinations of instrumental variables.

3.5. Results and evaluation of the models

3.5.1. Static model

Table 3.3 (a) and (b) summarize the result of the static models. The static model appears to fit the data well overall with p-values of coefficients are all significant at 1%. The null hypothesis of the Wald test that coefficients are zero are rejected at 1%, meaning that at least one of the coefficients is non zero in all time periods.

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variable in the dynamic model.

Table 3.3 Summary of the static model

	(a) Seven variables + EU dummy			(b) Four variables + EU dummy		
	1991-2014	1991-2000	2001-2014	1991-2014	1991-2000	2001-2014
	Coefficient	Coefficient	Coefficient	Coefficient	Coefficient	Coefficient
RI	0.0812 ***	0.1230 ***	-0.0538	0.0982 ***	0.1685 ***	-0.0122
	(0.000)	(0.000)	(0.232)	(0.000)	(0.000)	(0.792)
REEG†	0.0404 ***	-0.0224	0.0503 ***	0.0576 ***	-0.0074	0.0696 ***
	(0.002)	(0.246)	(0.004)	(0.000)	(0.736)	(0.000)
CO_2	0.2086 ***	0.1632	0.3431 ***	-	-	-
	(0.000)	(0.524)	(0.000)			
ED	0.0032 ***	-0.0004	0.0044 ***	0.0035 ***	0.0032 ***	0.0057 ***
	(0.000)	(0.779)	(0.000)	(0.000)	(0.000)	(0.000)
GDP†	0.2318 ***	0.6010 ***	0.1529	0.5295 ***	0.4882 ***	0.5608 ***
	(0.001)	(0.000)	(0.268)	(0.000)	(0.000)	(0.000)
IOP	0.1905 ***	0.0615	0.2441 ***	-	-	-
	(0.000)	(0.176)	(0.000)			
EC	-0.6093 ***	-1.3396 ***	-0.5483 ***	-	-	-
	(0.000)	(0.000)	(0.000)			
EU	0.1500 ***	-0.2646	0.2291 ***	0.4601 ***	0.4783 ***	0.3578 ***
	(0.002)	(0.282)	(0.001)	(0.000)	(0.000)	(0.000)
R-sq	0.5979	-	0.7573	-	0.6030	0.7865
sigma u	0.0000	0.2305	0.0000	0.1416	0.0985	0.0132
sigma e	0.1187	0.0688	0.0841	0.1237	0.0914	0.0862
rho	0.0000	0.9183	0.0000	0.5671	0.5374	0.0230
Wald Test	0.0000	0.0000	0.0000	0	0	0
Hausman Test RE>THRE	0.0000	-	0.0191	0.9926	-	0.0418
THRE>RE	-	0.0011	-	-	0.8332	-
Selected moel	RE	HTRE	RE	HTRE	RE	RE

P-values are in parenthesis.
† Assumed to be endogenous variables in Hausman-Taylor Estimation
RE: Random Effects model (General Least Squares)
HERE: Hausman-Taylor Estimation (random effects model)
*** significant at 1%; ** significant at 5%; * significant at 10%.

The Hausman test is conducted to determine whether the model is estimated by ordinary random effects model or the random effects model by Hausman-Taylor estimation that assumes endogenous variables. The results show that the Hausman-Taylor estimation is suitable in Period I of the estimation with seven variables and the EU dummy (Table 3 (a)), and in total in the simplified reference case with four variables and EU dummy (Table 3(b)).

As for expectation 1 on market reform, the RI has a positive relationship with the household electricity prices overall period and in Period I, and is statistically significant at 1% in both periods. This is interpreted to mean that lower electricity prices are generally associated with the progress of electricity market reform (a lower indicator of RI).

As for expectation 2 on environmental protection, A higher percentage of renewable energy in electricity generation results in a higher household electricity prices with the REEG significant at 1% in total and in Period II with higher coefficient in the Period II. CO_2 is statistically significant overall in Period II but not in Period I. The implications of these results are very interesting with respect to the environmental protection aspect of energy policy. Many developed countries are aiming to reduce CO_2 emission by introducing renewable energy, improving energy efficiency and reducing use of fossil fuel for tackling climate change issues. The model in this study works in a way that reducing CO_2 emission is associated with lower household electricity prices and increase of renewable energy is also associated with the increase of the household electricity prices. So, the effect of reducing CO_2 emission on household electricity prices is considered to be off-set if it is by means of increase of renewable energy. However, if the REEG's coefficients are decreasing or their signs are changing from positive to negative, this may imply that merit order of renewable energy is observed. Unfortunately, the reason for the slight differences in the coefficients of REEG and CO_2 is not clear which indicates they are more correlated with higher household electricity prices. The relatively higher REEG's coefficient in the Period II compared to Period I implies that the merit order effect on REEG has not yet been observed in this study.

As for expectation 3 on energy security, the authors found a positive relationship between energy dependency and household electricity prices overall and in Period II, although the coefficient is the smallest among the explanatory variables (1% increase of the ED is associated with 0.0032% in total and 0.0044% in Period II increase of household electricity prices).

As for expectation 4 on economic development, GDP and IOP have positive correlations with household electricity prices, of which GDP is significant at 1% overall and in Period I. The IOP is significant in total and in the Period II at 1%, but not significant in the Period I. The EC stays negative in total and both Period I and Period II, meaning that higher electricity consumption is associated with lower household electricity prices contrary to the expectation. As the model examines relationship but not causality, this may be understood that lower household electricity prices facilitate electricity consumption. A possibility for higher electricity consumption could be electrification. IEA pointed out the increasing demand of electricity in every field of energy use – heat and mobility in addition to the traditional end-use of electricity as a worldwide trend of electrification (IEA, 2017). The EU dummy is significant at 1% in total and in the Period II, implying that the static model captures homogeneity of EU member countries and heterogeneity with the outside-EU countries in this model at least in these periods.

Based on the above result, as a reference case the CO_2, IOP and EC variables were excluded from the Eq. (1). The authors found that this simpler model with four explanatory variables consisting of RI, REEG, ED and GDP and the EU dummy fits generally well enough, statistically significant at 1% level except for RI in the Period II and REEG in in the Period I. GDP and EU are two variables that have high coefficients.

3.5.2. Dynamic model

Table 3.4 summarizes the dynamic model with the three sub-categories.

Table 3.4 Summary of the dynamic model

	1) Level IV:RI, ED				2) Level IV: RI, GDP, ED				3) Level IV: RI, REEG, ED			
	SE		WCSE		SE		WCSE		SE		WCSE	
	Coefficient		Coefficient		Coefficient		Coefficient		Coefficient		Coefficient	
P_{t-1}	0.6700	***	0.6700	***	0.6212	***	0.6212	***	0.6707	***	0.6707	***
	(0.007)		(0.010)		(0.010)		(0.015)		(0.007)		(0.009)	
RI	0.3085	***	0.3085		0.3010	***	0.3010		0.3086		0.3086	
	(0.048)		(0.234)		(0.048)		(0.375)		(0.050)	**	(0.234)	
REEG	-0.0157		-0.0157		-0.0119		-0.0119		-0.0173		-0.0173	
	(0.897)		(0.945)		(0.921)		(0.961)		(0.885)		(0.930)	
GDP	1.6965	***	1.6965		1.6531	***	1.6531		1.6979	***	1.6979	
	(0.034)		(0.147)		(0.032)		(0.259)		(0.035)		(0.144)	
EU	0.4797	***	0.4797		0.5973	***	0.5973		0.4803	***	0.4803	
	(0.039)		(0.161)		(0.037)		(0.280)		(0.040)		(0.157)	
Wald test	0.000		0.000		0.000		0.001		0.000		0.000	
Sargan test	1.000		-		1.000		-		1.000		-	
AR(1)	0.049		0.121		0.059		0.227		0.049		0.121	
AR(2)	0.838		0.901		0.821		0.898		0.848		0.895	

P-values are in parenthesis.
SE: Estimation with standard error without the Windmeijer correction
WCSE: Estimation with the Windmeijer correction robust standard error
Sargan test is not available for the models with the Windmeijer correction for robust standard errors.
*** significant at 1%; ** significant at 5%; * significant at 10%.

In the dynamic model, generally estimations with standard error (SE) are good with p-values which are statistically significant at 1%, those with Windmeijer correction robust standard error (WCSE) yield the result that only the first lag of the dependent variable is statistically significant at 1%, showing strong path dependency, but generally not good results in other respects. Sub-categories of three different combinations of instrumental variables for level equation shows that overall trends of coefficients appear to have little difference, although in Table 3.4 the instrumental variables in the sub-category 2) RI, GDP and ED have less statistically significant p-values. These results imply that increasing sample countries is desirable as GMM assumes large samples.

The null hypothesis of the Sargan test that over-identifying restrictions are valid is not rejected. The null hypothesis of the Wald test that coefficients are zero is rejected at 1%, meaning that at least one of the coefficients is not zero. The null hypothesis of the autocorrelation test is that no autocorrelation in the error term of order 1 or 2. The results of the AR(1) are that estimation with standard error with Windmeijer correction (WCSE) are not rejected meaning no autocorrelation in error term in order 1 while those estimated without it (SE) are rejected meaning autocorrelation in order 1. The AR(2) showed the null hypothesis was not rejected in all sub-categories, meaning that no autocorrelation in error term in order 2.

As for the signs and values of coefficients, the first lag in the household electricity prices are from 0.6212 to 0.6707, which are significant at 1%. Such a strong path dependency is consistent with the result of the da Silva and Cerqueira. The coefficient of the GDP is the highest followed by the EU dummy and RI that are significant at least 5% in all sub-categories of SE, meaning that GDP's elasticity is the highest and most associated with the household electricity prices in this dynamic model. On the other hand REEG are not statistically significant in all sub-categories.

Explanatory variables with positive coefficients mean that the increase (decrease) of the dependent variable household electricity price is associated with increase (decrease) of the explanatory variable. Although the household electricity price is currently increasing, the model predicts that the household electricity price will decrease with a decrease in these explanatory variables especially the RI that is expected to decrease as market reforms advance in many countries.

In summarizing the results of the panel data analysis with the selected seven OECD countries for 1991-2014 by comparing the prior studies by Moreno et al., Hyland, da Silva and Cerqueira conducted on EU member countries, this study's static model portion is generally in line with Moreno et al.'s static model that electricity prices increase with the deployment of electricity generation from renewable and associated with the expansion of GHGs emissions (CO_2 emissions in this study) by energy related industries. With regard to the Hyland's study on the impacts on industrial electricity prices taking into endogeneity in the dynamic model, the authors showed that lower household electricity prices are also associated with the progress of electricity market reform while the relationship with the introduction of renewable energy is not statistically significant. Finally, as for the study by da Silva and Cerqueira on the drivers of household electricity prices, the dynamic model of this study is consistent with their conclusion that decreasing trend in prices is accompanied by electricity market reform. This study also supports their conclusion by showing that higher GDP is associated with higher household electricity prices and the coefficient is statistically significant. In spite of the path dependency, the result of the static model on the relationships of explanatory variables and dependent variable should be worth mentioned, at least qualitatively, minding the limitation of the dynamic model due to the number of the countries (N) used.

3.6. Conclusion

This paper has investigated the impacts of electricity market reforms and introduction of renewable energy together with other economic/energy security aspects in energy policy on household electricity prices using a set of panel data from 1991 to 2014 on seven selected OECD countries.

The dynamic model shows that household electricity price has a strong path dependency, and reforms in the electricity market are associated with lower household electricity prices that the energy policy originally aims to achieve. At the same time, the higher level of renewable energy is not clearly associated with higher household electricity prices. The household electricity price is higher with higher regulatory index, although the GDP's coefficient is the highest, when the lagged variables are set aside.

The authors concluded that evolution of regulatory reform does bring lower household electricity prices and has more impact on the increase of household electricity prices than the increase of renewable energy does.

The model does not clearly show the effect of merit order with the increasing renewable energy deployment, although renewable energy is more likely to be used in a fully developed electricity exchange market by merit order as the introduction of renewable energy further proceeds. Unbundling and establishment of a real-time electricity transaction market enables acquisition of electricity in merit order. This has potential impact to clearly lowering electricity prices in the future. The other elements of deregulation such as privatization of national electricity companies do not bring about this advantage. Careful observation and examination on the impact of the further introduction of renewable energy to the electricity price is required.

A further study covering more countries would likely help evaluate the effects of the explanatory variables on the dependent variable more in detail as the GMM assumes large samples. For instance, by having more countries both within EU and outside EU countries in the panel data model, it may be possible to evaluate two groups of countries (EU member countries and non-EU member countries) with different energy policy situations rather than by introducing a EU dummy variable. It may also be possible to examine differences in groupings of countries such as by GDP, energy dependence and connection to a continental grid system. For estimation with small N (in this study, the number of countries), Maximum Likelihood Estimation (MLE) is another method that can be applied for data set with small N relative to T (time series). However, caution should also be paid even in using MLE that necessity of identifying a probability density function for the likelihood function, and initial values do influence the results of the estimation. As for the identification of a probability density function, effective estimation is still possible even when the true probability function is not identified but a mis-specified function is used for some conditions, as called quasi-MLE (Namba, 2015). As for the initial value, setting the timeline is relatively easy in case of planned experiments in a laboratory or in field work, but not the case for nations. Nations or countries exist historically in different conditions and their activities are continuous. In any case, when using GMM, MLE or other estimation methods, application of these analytical methodologies in econometrics and statistics scenarios to the real world cases requires paying attention to the available sample size. It will be possible to obtain large N - hundreds, thousands or sometimes tens of hundreds of households and individuals. But it is not the case for nations which N is at most 200 and even limited according to the purpose of study and data availability. In case of international panel data analysis for energy policy, it inevitably requires internationally comparable, continuous and a reliable country energy data set. Even for the 30 IEA member countries, very basic data like some historical electricity prices are not publically available for some countries. The existing study of Moreno et al., Hyland and da Sylva and Cerqueira focused on EU member countries but they did not encompass non-EU countries like United States, Canada and Japan important in terms of analyzing difference and commonality of energy policy. Berrar (2017) pointed out that it is important to look beyond p-values, and also consider effect size as well as the context of the study – the meaning of the result in field that is being analyzed.

It should be also noted that a longer time range utilizing the dynamic model could potentially clarify whether a clear, statistically significant structural change has taken place and when such a structural change was clearly observed. Finally, application of dynamic stochastic general equilibrium (DSGE) model to this field of research has been limited so far and will be very valuable as future research. DSGE can model behavior of electricity prices with control of change of technology that impacts business cycle and investments. It will be expected to provide insights for more theoretically backed explanations on the relationship between electricity prices, market reforms and introduction of renewable energy. Future work should encompass careful examination of GMM, MLE and DSGE methods.

In terms of the role of renewable energy in electricity generation, the wider implications of Chapter 2 is that the role of renewable energy has modest expectations in the Japanese future electricity mix of 2030, leaving a more ambitions electricity mix with higher renewable energy. The panel data model in Chapter 3 with regards to renewable energy introduction remains mixed while the electricity market reform is generally statistically significant on the increase of household electricity prices. Focusing on Japanese energy supply through Chapters 2 and 3, inhibiting factors or geographical peculiarity that Japan is an isolated island country should be mentioned as they effect energy mix and energy infrastructure such as electricity grid system and LNG terminal. Unlike continental Western European countries whose natural gas are supplied through pipelines from Russia and Africa, Japan's import of natural gas is liquefied natural gas supplied by ships, which is about 1.5 times more costly compared to natural gas supplied to Europe (Japan Institute of Country-ology and Engineering (JICE), 2016). Japan's electricity grid system is also closed within the country, not connected to a continental grid system. As some of high-voltage transmission grid system over regional monopoly areas of originally vertically integrated ten utilities companies had received little investment, the 3.11 accident necessitated power interchange among utilities in order to balance the very tight supply-demand of electricity. However, capacity of power electricity interchange in balancing electricity demand and supply in Japan is likely to be limited compared to that of a large continental European electricity grid system. In particular, as the electricity from renewable energy such as PV and wind are generated depending on weather conditions but not with regard to the change of demand, it is more difficult in a small grid system to handle the change of electricity generated from such intermittent, unstable sources of generation compared to a larger grid system. In order to increase use of renewable energy in Japan, the Government is going to promote investments such as on transmission grid system for the electricity interchange over regional utilities and concurrent use of battery storage (Agency for Natural Resources and Energy (ANRE), 2014).

Chapter 4: General Conclusions

Energy policy is one of the most important policy areas facing national governments. The world energy outlook shows that global increase of energy consumption, progress of electrification and transition to a cleaner energy society with more renewable energy introduced. As more and more energy is supplied as electricity in all region of the world, both in developed and developing countries, energy policy regarding electricity needs more attention and intensive research. Among others, a national government's choice on electricity mix and determinants of electricity prices are energy policy topics that typically requires to manage energy policy trade-offs such that prioritizing economic growth rather than environmental protection or safety in the decision-making of an electricity mix. Electricity is versatile for any use of energy as power, lighting, heating and cooling, and even mobility without direct emission of pollutants at the end-use. The choice of the electricity mix will be more important than ever for a national government. Cherp et al. studied a historical analysis evolution of nuclear, wind and solar power in Germany and Japan. They found that the energy paths of the two countries were remarkably similar in the 1970s-1980s but Germany has become a leader in renewable energy whereas Japan continued development of nuclear power rather than renewable energy. They pointed out the difference came from the speed of growth of energy demand and level of energy security (demand grew faster and energy supply is less secure in Japan), easier diffusion of wind power and competition of energy industries (easier diffusion and strong coal industry compared to nuclear in Germany) (Cherp et al., 2017). The path to more electrification and a cleaner energy society is all in all different in each country. National governments also need to understand complicated effects of policy measures aimed to achieve different policy goals such as introduction of renewable energy and electricity market reforms on electricity prices. The level of electricity prices are also determinants of the effects of other energy policies such as ensuring investment in the energy infrastructure. The California Electricity Crisis in 2000 and 2001 is considered due partly to the liberalization of electricity market with capped retail sales prices that hindered enough investment for electricity infrastructure to cover the growing electricity demand while avoiding the obligation to purchase electricity generated from energy sources with less environmental burden (Sweeney, 2008).

The previous chapters have examined two topics utilizing scientific approaches to these major energy policy themes on electricity. A three-layer AHP model with two opposing views on safety was introduced in order to compare and analyze three electricity mix scenarios after the 3.11 nuclear accident in Japan, and a panel data model was constructed to analyze the impacts of ongoing electricity market reform and increase of renewable energy on household electricity prices.

The results of the AHP model show that the highest nuclear power proportion scenario (20% nuclear in the generation mix) among three electricity mix scenarios is the most appropriate when safety is measured with human fatalities as a scientific measurement of risk. This may appear contradictory to the high public preference of eliminating nuclear energy in Japan, the statistically low human fatalities, when scaled to electrical power generated, indicates that it is the safest electricity generation mix. This study clearly revealed that opposing viewpoints on safety result in choosing different electricity generation mixes and showed the effectiveness of scientific approach to policy decision-making. The multiplicity of AHP model enables policy-makers to arrange the model suitable to any country with a variety of scenarios, and successfully provides a sufficiently general structure for evaluating electricity mix scenarios with 3Es and safety, where different views on safety or any other criteria can be incorporated and compared even though these criteria cannot be measured in a same metrics.

The panel data models show that household electricity price has a strong path dependency in dynamic model with a lagged variable, and reforms in the electricity market is associated with lower household electricity prices that the energy policy originally aims to achieve. The higher level of renewable energy and is also associated with higher household electricity prices in static models but not statistically significant in dynamic models. Although the model does not clearly show, renewable energy with low marginal costs is more likely to be used in a fully developed electricity exchange market by merit order as the introduction of renewable energy further proceeds. Pollitt once admirably noted the challenge for policy-makers within a liberalized environment was that the costs of ambitious climate change policy goals would be increasingly obvious to energy consumers (Pollitt, 2012). A deregulated market with unbundling and establishment of real-time electricity market will enable the least marginal cost acquisition of renewable energy at low costs in merit order in the future. A further study covering wider countries, a longer time range utilizing the dynamic model is needed to observe a clear, statistically significant structural change that electricity prices go down as a result of the decreasing trend of costs of renewable energy, and when such a structural change will happen. As GMM assumes large samples, covering wider countries enables more detailed examination of effects of explanatory variables by grouping countries with EU/non-EU countries, GDP and so on.

As a possible future work, is applying the dynamic stochastic general equilibrium (DSGE) model to this field of research may also be very valuable. It can model behavior of electricity prices with control of change of technology that impacts business cycle and investments and provide insights for more theoretically backed explanations on the relationship between dependent and explanatory variables.

We believe that various extensions of the panel data models are also possible. Future work should also include examination of other explanatory variables, such as introducing dummy variables (when FIT is introduced), detailed decomposition of regulatory index. Changing the dependent variables from household electricity prices to the ration of household electricity prices to industry prices will also provide perspective on the difference of the effects of the explanatory variables to width of the household/industry electricity price gaps. Examination of causality relationship between explanatory variables and dependent variables.

Applying these two scientific approaches to energy policy on electricity allows policy-makers to understand, quantitatively analyze the complexity of energy policy.

It may also be challenging but worth trying to apply these scientific approaches to developing countries. Although developing countries often have constraints related to data collection, democratic decision-making and available policy resources such as capital for investment or regulatory infrastructure, most of the growth of energy consumption and GHG emission will take place in these countries, and their paths to the cleaner energy society can be different from those of developed countries.

Finally, implications to Japanese energy policy obtained from this research are follows. First, the three scenarios proposed by the Japanese Government were modest scenarios especially in introduction of renewable energy. More ambitious scenarios can be examined with the AHP models constructed in this research. It should also be pointed out that the use of thermal energy is an important part of energy policy along with electricity and less explored in Japan. Some type of renewable energy such as geothermal, biomass and unused energy like temperature difference energy (thermal electric devices) can be more efficiently used with its thermal energy rich local areas. This is a theme of energy mix policy with broader perspective not limited to electricity mix policy. The AHP model can easily be extended to energy mix. Second, clear identification of trade-offs in energy policies and measures is a basis for democratic policy making and implementation. Using environmentally-friendly renewable energy has trade-off of costs and stable supply compared to other energy sources. Policies and measures are inter-related as seen the relationship of explanatory and dependent variables in the panel data model in Chapter 3. Scientific approach can contribute to elucidate such trade-offs. Third, energy infrastructure and the use of energy require high technological achievements, affordability and social acceptance. Any energy policy and measure lacking these elements cannot serve as reliable instruments for the sake of society. Scientific evaluation of policy and measures is more important than ever as Japan is targeting an ambitious 80% reduction of GHGs emission by 2050 in response to the Paris Agreement's objective to keep a global temperature rise this century well below 2 degrees Celsius (The Government of Japan, 2016).

Appendix

A-1 Unit root test and cointegration test for time series data

In the preparation for any use of time series data, we need to unit root test and if there is any unit root, cointegration test. The reason why it is important to check weather a time series data are stationary or nonstationary before conduction any regression analysis because there is a danger of obtaining apparently significant regression results from unrelated data when nonstationary series are used in regression analysis. This kind of regression are said to be spurious (Hill, Griffiths, & Lim, 2011). It is appropriate to use the data if it is stationary after unit root test. If it is nonstationary, lagged variable (dependent or independent, at least one) should be included in the model to avoid spurious regression (Okimoto, 2010).

In an autoregressive model y_t with time lag of one expressed as AR (1),

$$y_t = \rho y_{t-1} + v_t$$

$$y_t - y_{t-1} = \rho y_{t-1} - y_{t-1} + v_t$$

$$\Delta y_t = (\rho - 1) y_{t-1} + v_t$$

$$\Delta y_t = \gamma y_{t-1} + v_t$$

Where $\gamma = \rho - 1$ and $\Delta y_t = y_t - y_{t-1}$, the first difference of y_t

The null hypothesis of the unit root is that the series is nonstationary.

H_0: $\rho = 1$ ⟷ H_0: $\gamma = 0$

meaning, the AR(1) model y_t has unit root and nonstationary

H_1: $\rho < 1$ ⟷ H_1: $\gamma < 0$

meaning, the AR(1) model y_t does not have unit root and stationary

If we do not reject the null hypothesis, we conclude that it is a nonstationary process; we reject the null hypothesis that γ= 0, then we conclude that the series is stationary. The results of the Dicker-Fuller Test as unit root test for each time series data of each of seven countries in the Chapter 3 are follows in the Table A-1. The Dickey-Fuller unit root test shows most of the series are nonstationary. So, lagged variables are needed in model.

Table A-1 Results of the Dicker-Fuller Test for data in Chapter 3

	P		REEG		GDP		ED	
	statistics	p-value	statistics	p-value	statistics	p-value	statistics	p-value
Japan	-1.281	0.846	-1.357	0.817	-2.393	0.422	0.051	0.990
Germany	-1.573	0.735	0.444	0.990	-1.492	0.766	-3.686	0.044
France	-1.102	0.906	-0.864	0.941	-1.555	0.742	-0.118	0.990
UK	-1.370	0.813	3.610	0.990	-1.758	0.665	-3.396	0.078
US	-1.916	0.604	-0.783	0.951	-1.337	0.825	1.644	0.990
Italy	-1.459	0.779	1.596	0.990	-1.505	0.761	-0.535	0.972
Canada	-2.324	0.449	-0.568	0.969	-1.918	0.603	-0.551	0.971

	CO_2		IOP		EC		RI	
	statistics	p-value	statistics	p-value	statistics	p-value	statistics	p-value
Japan	-2.740	0.291	-2.179	0.504	-1.166	0.890	-0.496	0.975
Germany	-3.290	0.093	-2.179	0.504	-1.221	0.869	-1.503	0.762
France	0.055	0.990	-2.179	0.504	1.315	0.990	-0.672	0.961
UK	0.063	0.990	-2.179	0.504	0.073	0.990	-1.844	0.632
US	-0.808	0.949	-2.179	0.504	-1.012	0.919	-2.636	0.330
Italy	1.257	0.990	-2.179	0.504	0.829	0.990	-1.350	0.820
Canada	-0.493	0.975	-2.179	0.504	-1.350	0.820	-1.477	0.771

A-2 Correlations of data in the Chapter 3

It is also necessary to check data correlations of each time series to avoid multicollinearity. Table A-2 shows the correlations, and strong correlations such as Electricity consumption (EC) - CO_2 emission, international oil prices

(IOP) – GDP are observed. It implies a need to reduce parameters to a minimum in the model.

Table A-2 Data correlations

	REEG	GDP	ED	CO_2	IOP	EC	RI
REEG	1.000						
GDP	-0.049	1.000					
ED	**-0.601**	0.054	1.000				
CO_2	0.346	0.093	**-0.583**	1.000			
IOP	0.121	**0.792**	0.055	-0.117	1.000		
EC	**0.596**	0.211	**-0.660**	**0.832**	0.055	1.000	
RI	0.382	**-0.656**	-0.139	-0.070	**-0.511**	0.017	1.000

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