# A Quantitative Study on Innovation in Renewable Energy Technology in Korea

（韓国の再生エネルギー技術における革新の定量的研究）

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Dissertation for the fulfilment of the
Doctoral program in Global Environmental Studies

Kyoto, Japan, March 2017

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# Abstract

Korea is one of largest countries of energy consumption and emitter of greenhouse gases (GHGs) that influence on climate change. In addition, the energy security is also a major political issue in the country owing to heavy dependence on overseas' fossil fuels and nuclear power that has safety and environmental concerns. Therefore, the infinite and clean renewable energy technology has been newly introduced and "Low Carbon and Green Growth" was proclaimed as the nation's vision in 2008. "4th basic plan for the promotion of the development, use and diffusion of new and renewable energy (2014~2035)" has been implemented since 2014, aiming at increasing the use of renewables to 11% of Total Primary Energy Supply (TPES).

Research objective of the current dissertation seeks to assess the R&D efficiency in Korean renewable energy technology and changes in price of the technology with quantitative approach. Data Envelopment Analysis (DEA) is used to estimate the efficiency of R&D productivity by performer and by technical progress phase. Secondly, the future Korean PV module and generation price by 2035 to verify if the forecasted prices will reach the national targeted generation prices with the current level of production and R&D support.

The result shows that while the efficiencies on basic and applied research are rather high in most performers, since direct outputs from R&D support are sufficiently created, most research on the development phase correlated to profitability performed mostly by firms are rather inefficient. In addition, the efficiencies on the development phases show the efficiency in the smaller firms is slightly higher than large firms that received the R&D support the most in amount as well as per project. The PV target generation price, according to the Fourth Basic Plan for New and Renewable Energy released in 2014, is expected to reach KRW 245.75/kWh by 2017, KRW 117.6/kWh by 2022, and KRW 60.9/kWh by 2035. The anticipated PV LCOE is not expected to reach the 2022 goal, but will decline to KRW 60.9/kWh of the 2035 PV target price by 2032 and decrease to KRW 31.043 ~ 39.917/kWh by 2035.

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# 1 Introduction

## 1.1 Research background

Renewable energy technology is defined "*the technologies that enable constantly replenished renewable energy flows to be harnessed to produce power in forms useful to humanity on a sustainable basi*s" (Boyle, 2010). With increasing issues on climate change and energy security, the infinite and clean renewable energy technology has been appeared to be one of effective solutions on rising to these challenges. The renewable energy including bio energy, geothermal energy, hydropower, ocean energy, solar photovoltaic (PV), wind power and any other energies that do not emit greenhouse gases (GHGs) or harm environment are converted as various types of energy according to its usages like electricity, heating and cooling energy or fuels used for transportation.

### 1.1.1 International movements towards climate change mitigation and renewable energy use

There are three large drivers of innovation in renewable energy technology, which are climate change, energy security, and economic growth as shown in the figure 1.1. The efforts on responding the demand of non-conventional resources through innovation in the energy system has been emphasized during the last two decades for climate change and energy security. The United Nations Climate Change Conference (UNCCC) entered into force in 1994 with an aim of preventing "dangerous" human interference with the climate change. The 197 countries have ratified the convention at current and are referred as Parties to the Convention. The convention holds the Conferences of the Parties (COP) since 1995 to assess progress in coping with climate change. One of remarkable accomplishments by the convention is to adopt the Kyoto Protocol in the COP 3 convened in Kyoto in 1997. The Protocol that entered into force in 2005 applies a notion of "common but differentiated responsibilities", which namely the 39 parties categorized as Annex I countries are more responsible for the climate change. Those countries signed to devote to reducing GHG emissions[1] to an average of 5.2 percent against 1990 level between 2008 and 2012.

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[1] The main GHGs treated at the Kyoto Protocol for the first commitment period are Carbon dioxide ($CO_2$), Nitrous oxide ($N_2O$), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs) and Sulphur hexafluoride ($SF_6$)

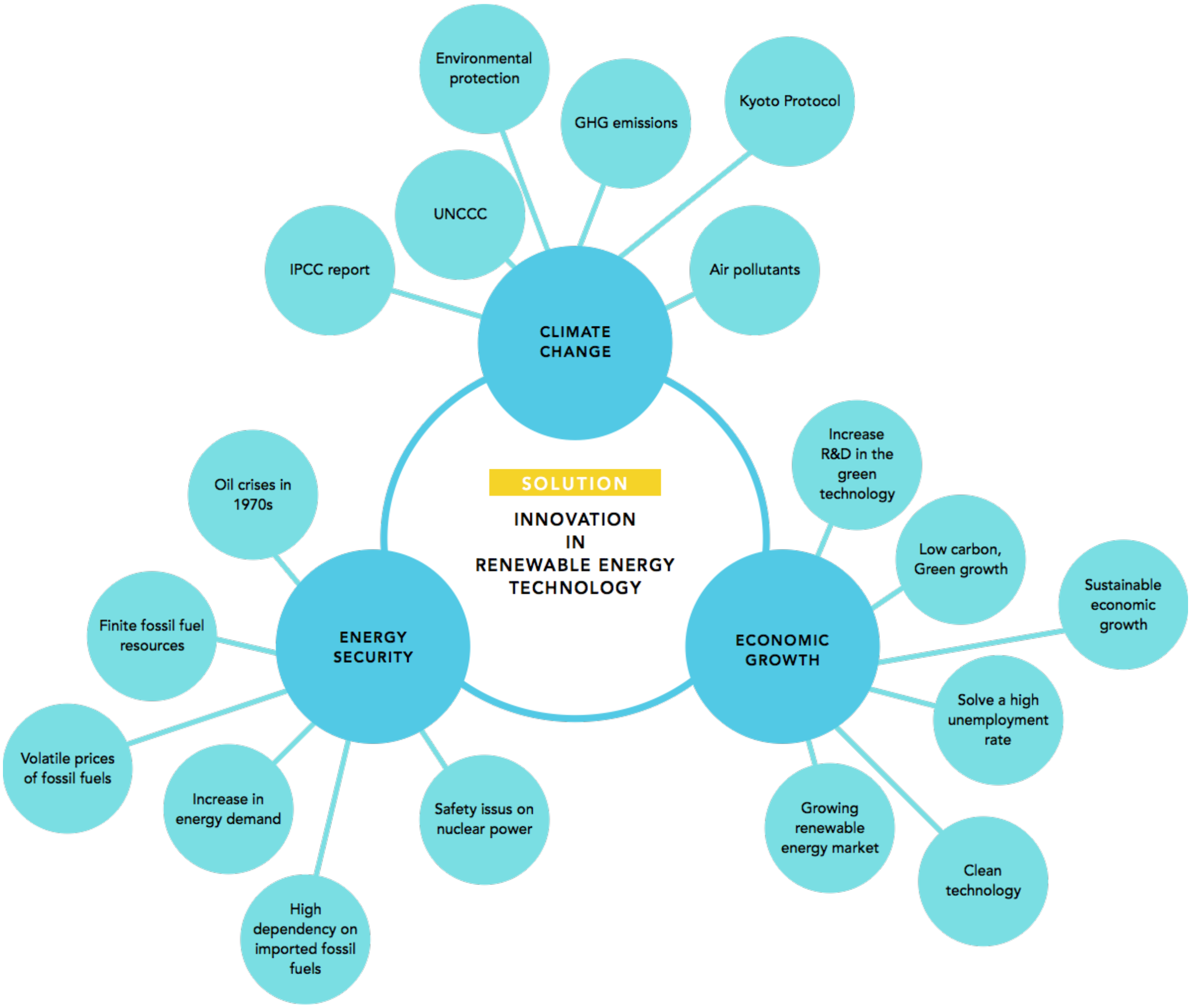



Figure 1.1. Drivers of innovation in renewable energy technology

The Kyoto protocol requires the developed countries to implement domestic Policies and Measure (PAM) and allows to use "flexibility mechanisms" of International Emission Trading (ET), Joint Implementation (JI), and Clean Development Mechanism (CDM) to supplement PAM. ET enables Annex I Parties to trade the assigned amount of emissions each other during the commitment period. JI permits Annex I Parties to carry out projects that reduce GHGs by source or improve removal by "sinks" in the territories of other Annex I Parties and credit the resulting Emission Reduction Units (ERU) that permits to offset their own emission amount to reduce. Lastly, CDM allows Annex I Parties to implement projects relevant to the reduction in GHG emissions in the non-Annex I Parties.

In COP 18 in 2012, the Doha Amendment to the Kyoto Protocol was made, and the commitment period was extended by 2020 for Annex I Parties who continue to take on commitments to reduce GHG emissions during the extended second period from 2013 to 2020 and the Parties committed to reduce GHG emissions by at least eighteen percent below 1990 levels. There are 192 Parties to the Kyoto Protocol to the UNFCCC as of 2016. In COP 21 in 2015, the Paris Agreement[2] was adopted to deal with GHG emissions mitigation, adaptation, and finance starting in the year of 2020 and has not entered into force yet.

A remarkable progress was made for renewable energy technology in COP 9, which took place in New Delhi in 2002 when "Delhi Ministerial Declaration on Climate Change and Sustainable Development" was adopted. The declaration includes the requirements to develop cleaner, more efficient and affordable energy technologies and necessary actions to increase use in sustainable renewable energy sources that seldom generate GHG emissions. Accordingly, it is expected that renewable energy technology will brighten its prospect to be widely used, reduce GHG emissions and finally deal with climate change in the energy system.

### *An international investment trend onto renewable energy technology*

The new installation of international renewable energy in 2015 reached 133GW increased by 29.1% compared with the previous year despite global economic recession and low oil price (Park J. , 2015). Accordingly, new investment increased to peak by

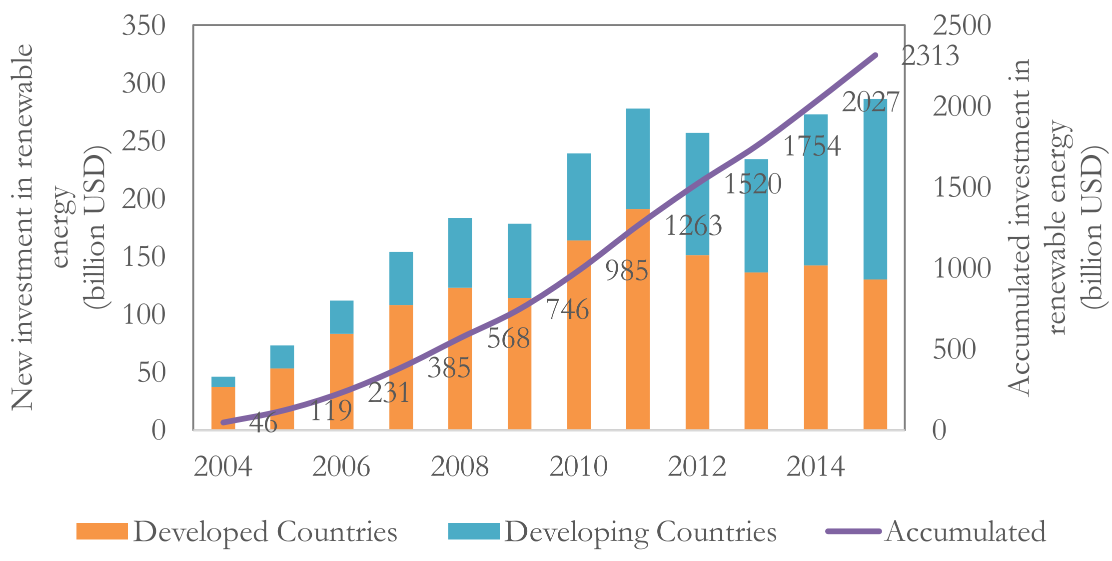
[2] According to Article 21 of the Paris Agreement, "The agreement shall enter into force on the thirtieth day after the date on which at least 55 Parties to the Convention accounting in total for at least an estimated 55 percent of the total global greenhouse gas emissions have deposited their instruments of ratification, acceptance, approval or accession."

USD 329 billion and the trend is likely to continue in response to global climate change with a strong political will of countries and technological development in renewable energy that can substitutes coal power plants in the energy mix. In addition, the renewable industry will experience a rapid growth in production as the grid parity primarily in PV and wind energy is realized in many countries and the technological development in Energy Storage System (ESS) that devised due to intermittent and unstable characteristics of renewables. The international average rate of annual supply from 1990 to 2012 is 46.8% in PV, 24.9% in wind energy and 14.3% in biogas.

Total international investment in power and fuel sectors of renewable energy, excluding hydropower project whose scale is larger than 50MW and renewable heating and cooling technologies, made between 2004 and 2015 was USD 2,313 billion, as shown in Figure 1.2 (Frankfurt School-UNEP Centre/BNEF, 2015). The investment from developed countries has been on a downward trend in 2012 and 2013 mainly due to the United States where the treasury grants and federal loan guarantee programs for renewables were expired in 2011. However, the investment has increased slightly again since 2014 with boom in solar power installation in Japan and offshore wind projects in Europe.

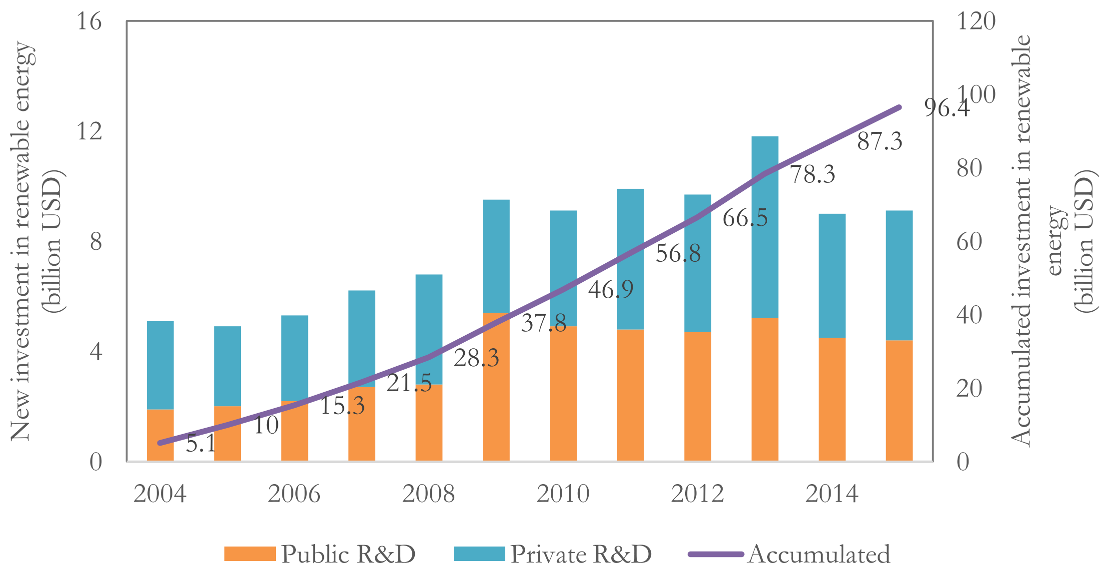
On the other hand, the developing countries that include China, Brazil, and India shows sharp increase in the investment to the renewable energy technologies with USD 83.3 billion of Chinese large investment in 2014 that accounts for nearly one-third of the international investment in renewable energy. In 2015, the investment slightly increased by USD 286 billion, adding USD 13 billion compared to the previous year.

Figure 1.3 shows the international public and private R&D investment trend in renewable energy technology between 2004 and 2015. Nearly 4.2% of total international investment for renewable energy technology is used for the sake of R&D activities in renewable energy technology during the period. The increased R&D in 2013 was largely due to USD 1.3 billion of increased spending on solar energy, USD 400 million on wind energy and USD 500 million on biofuels, which almost half of the additional investment is from Europe and Asia-Oceania region (Frankfurt School-UNEP Centre/BNEF, 2015). Despite recent falling price in fossil fuels in 2015, spending on R&D is slightly increased by USD 100 million in total. Solar energy dominates renewable energy R&D, accounting for 47.2% of total R&D between 2010 and 2015, followed by biofuels, wind energy, biomass and waste, small hydro,



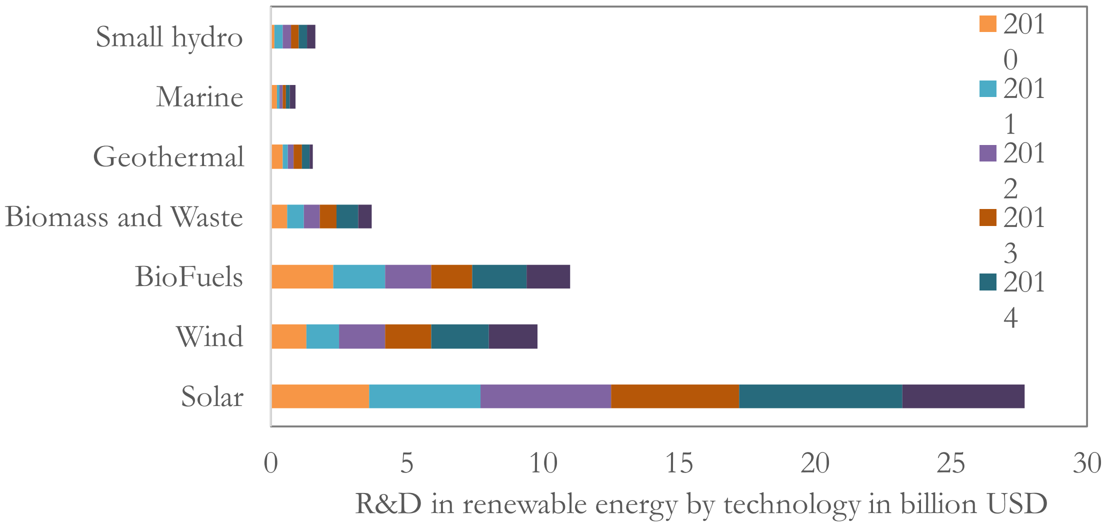

Source: Frankfurt School-UNEP Centre/BNEF (2015)

Figure 1.2. International investment in renewable energy in developing and developed countries



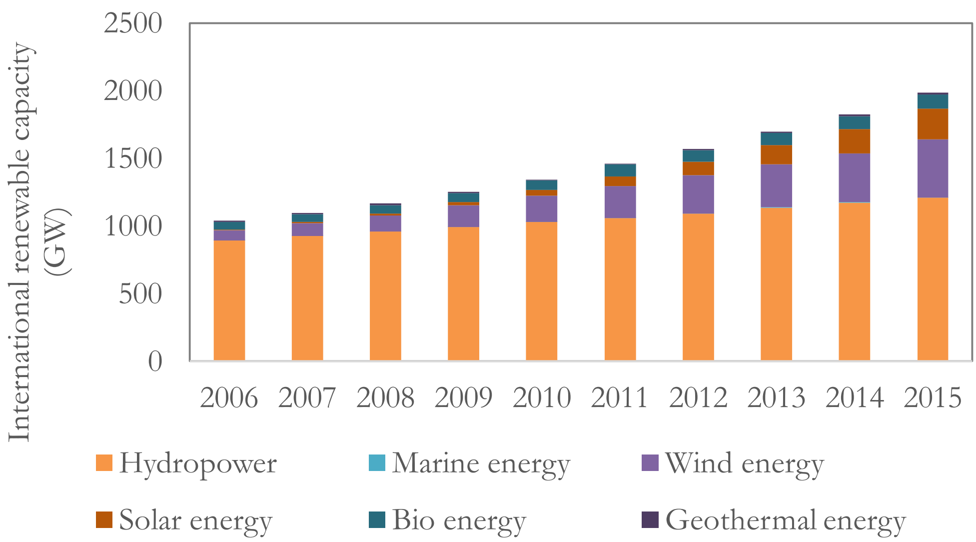

Source: Frankfurt School-UNEP Centre/BNEF (2015)

Figure 1.3. International public and private R&D investment



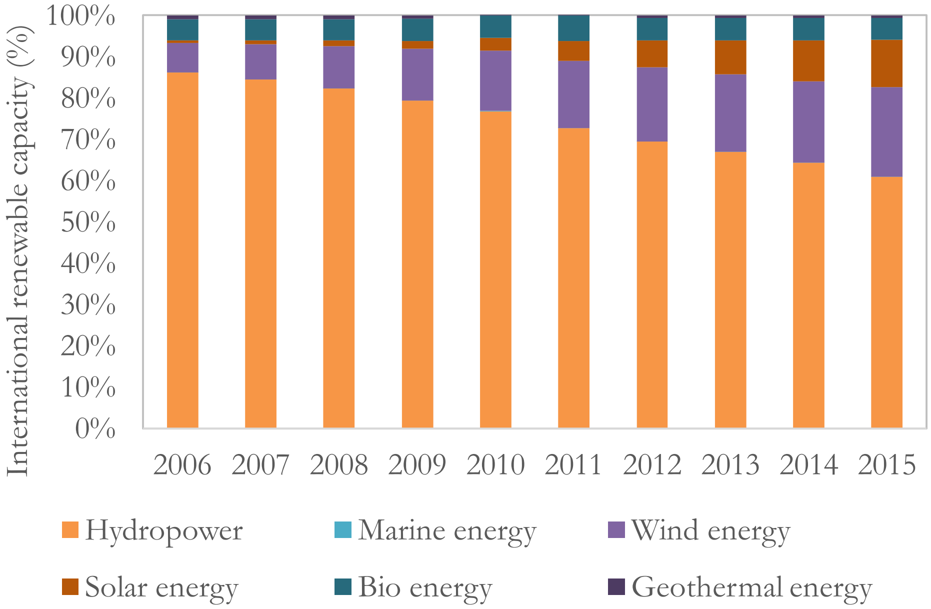

Source: Frankfurt School-UNEP Centre/BNEF (2015)

Figure 1.4. R&D investment by renewable energy technologies from 2010 to 2015




Source: IRENA (2016)

Figure 1.5. International renewable capacity by energy sources (GW)




Source: IRENA (2016)

Figure 1.6. International renewable capacity by energy sources (%)

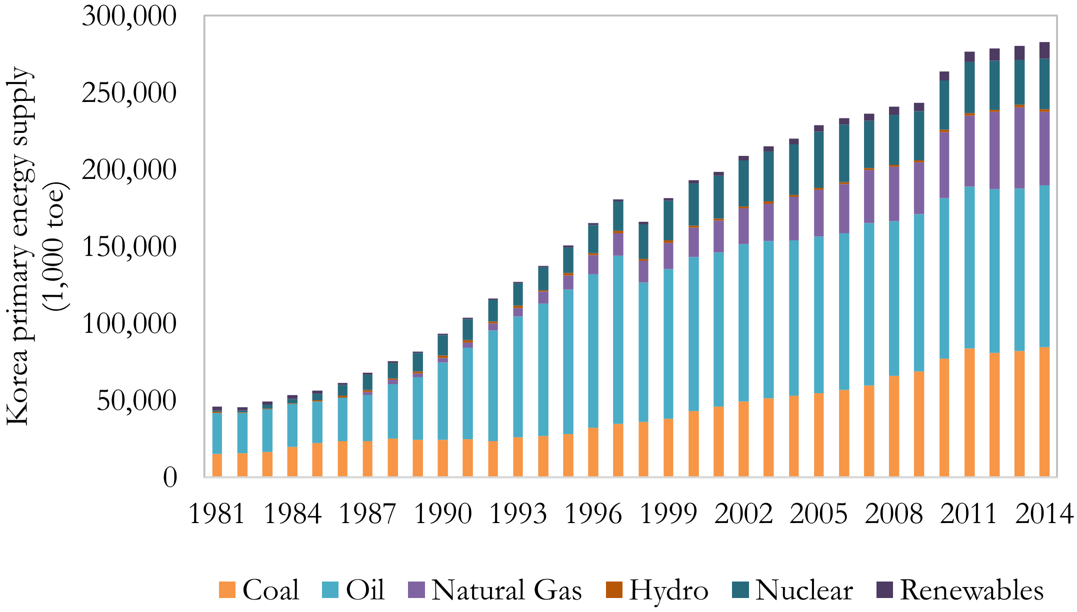
geothermal and Marine as shown in Figure 1.4. (Frankfurt School-UNEP Centre/BNEF, 2015).

The renewable energy capability depends both on natural condition and its technological. The international renewable capacity is described in Figure 1.5 The capacity increased from 1,036 GW in 2006 to 1,985 GW in 2015 during a last decade, corresponding to an average growth rate of about 7.49% per year. Figure 1.6 depicts the international renewable capacity as a percentage by energy sources. The hydropower, that typically occupies a large share of renewable capacity, accounts for 60.9% in total renewable capacity in 2015 and followed by wind 3energy (21.76%), solar energy (11.44%), bio energy (5.22%), geothermal energy (0.66%), and marine energy (0.03%) in the same year.

### 1.1.2 Continuous increase in energy demand and debate on use of nuclear power plants in Korea

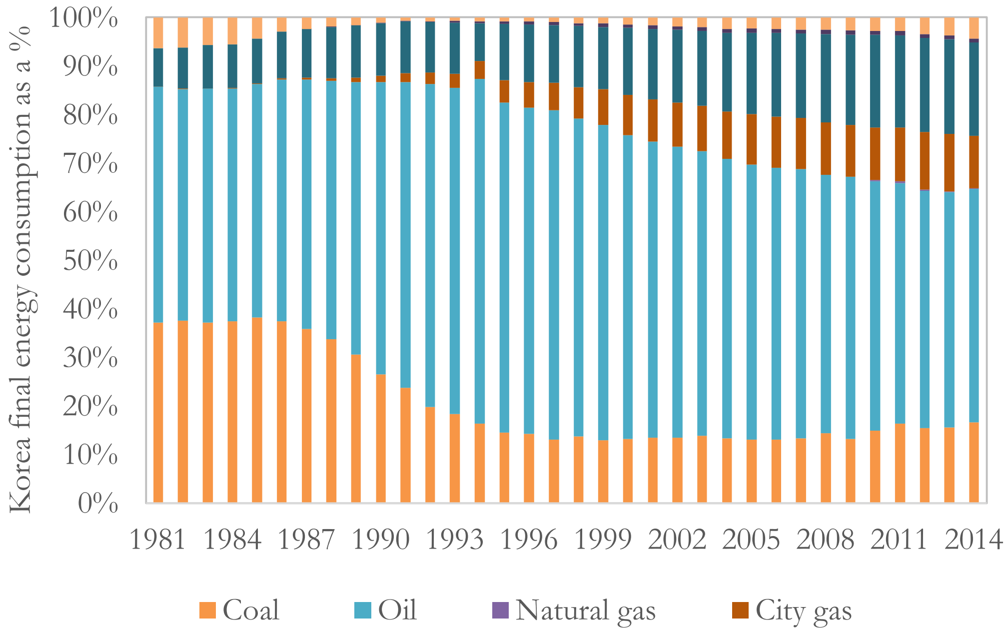
Energy use in Korea will keep increasing amid rising concerns on energy security as a country that is nearly dependent on the imported energy sources for domestic use in industries and households as well as a high demand from international society towards a responsibility for the GHG emissions as a country that emits 592499.19 kt of CO2 emissions in 2013 that places $8^{th}$ in the world (World Bank, 2016). While new construction of several nuclear power plants has been planned despite its safety and environmental problems, the country has also begun to take a profound interest in renewables use for one of energy supplies. However, several countries like EU countries and the United States have shown the noticeable growth in using renewables as energy sources with strong political, legal and financial supports within each countries, Korea struggles for expanding share of renewables within domestic energy mix as well as develop renewable technologies by being competitive in the international market.

Korea has several large industries of steel, oil and chemicals, and semiconductors, which intensively consumes energy and emits GHGs much, and provides those industries with a benefit to use less expensive electric than households. The energy supply in Korea shows a constant rising trend with 5.7% of an average growth rate from 1980 to 2014 except for the year of 1998 when Korea experienced financial crisis as shown in Figure 1.7. In 2014, the total primary energy supply is 282,937.7 thousand toe and the uptrend in energy supply is expected to continue according to an increasing energy demand along with economic growth.




Source: KESIS (2016)

Figure 1.7. Korea primary energy supply




Source: KESIS (2016)

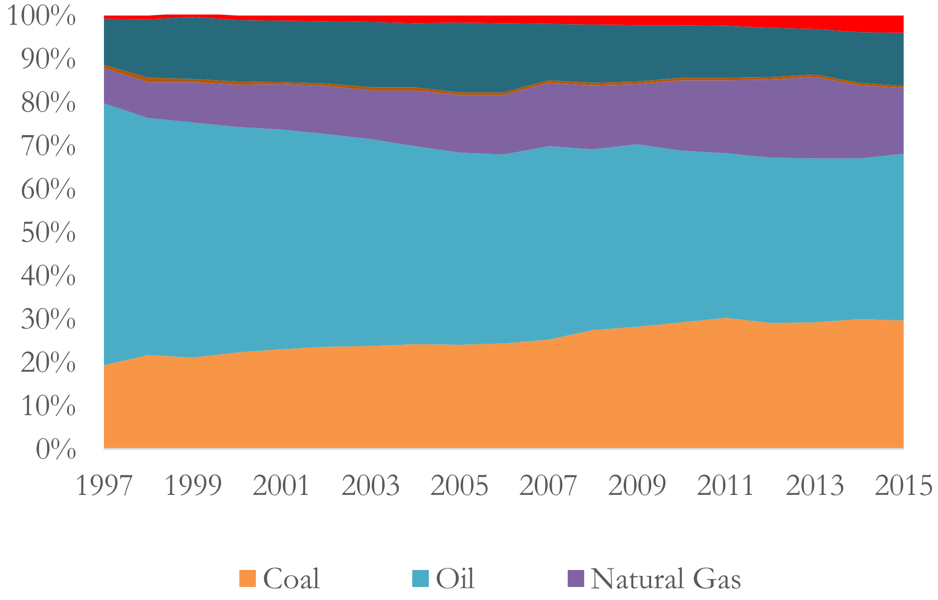
Figure 1.8. Korea final energy consumption

The total final energy consumption is 213,869.6 thousand toe, as depicted in Figure 1.8., which placed the country as 8th largest energy consuming country that uses 1.56% of the world energy (Enerdata, 2016). The fossils fuels of coal, oil, and natural gas accounts for 64.9% of the total final energy consumption. The electricity occupies also 19.2% of large share of the energy consumption, which comes largely from thermoelectric or nuclear power plants. The energy consumption by renewables in 2014 is 9,466.4 thousand toe, which accounts for 4.4% of the total final energy consumption.

The energy security has been a major political issue that should be taken care as a national issue for Korea like all other countries; however, as a country that limits domestic fossil fuel reserves, it is heavily dependent on overseas imports of fossil fuels and on nuclear power. The conventional energies, fossil fuels and nuclear power, comprised 95.5% of Korea primary energy supply as of 2015, as shown in Figure 1.9, which implies the energy risk in the country may be largely influenced by external factors such as oil crises once experienced in 1970s and the high oil price that will steadily increase in the future. In addition, the domestic rapid energy consumption with 2.7% of annual average growth between 2013 and 2018 is playing a role as an internal factor (Ministry of Trade, Industry and Energy, 2014). It is significant to secure energy sources without any troubles all the time for economic development as well as social stability.

Nuclear power has appeared to be a practical choice and solution for Korea to deal with issues on stable increase in energy consumption and energy overseas dependency. In addition, it is considered as a countermeasure to prepare a debate related to the Climate Change Convention and the reduction in GHG emissions. Total 20,716 MWe of twenty-three nuclear reactors in seven power plants are being operated, which accounts for 22.2% of total electricity capacity. Nuclear power produced 156 TWe in 2014, comprised 30% of total national electricity generation (Ministry of Science, ICT and Future Planning, 2015). Its share will increase by 29% in 2035 according to the second National Energy Basic Plan established in 2014.

However, the safety and environmental concerns on nuclear power plants are also controversy in the country whose share of nuclear power is one-third of total electricity supply. Negative criticism on nuclear power is greatly growing especially after Japanese Fukushima Power Plant accident in 2011 and several breakdowns of domestic over 30-year-old reactors. Considered average design lifetime of nuclear reactor is 30 years,




Source: Korea Energy Statistics Information System (KESIS) (2016)

Figure 1.9. Korea primary energy supply

nuclear power reactor that reaches the end of life within 10 years in Korea are six (Kim J. , 2015). Old reactor causes frequent breakdowns and stability issues and there is a large controversy and demand in the society that the old reactors should close immediately. In addition, problems on the reactors' decommissioning and the radioative waste disposal also remains to be solved, which requires high financial expenditure as well as a consideration on environmental impact.

Nuclear power cannot be a long-term solution for the energy source due to its safety issues and environmental impact. There was a serious of earthquake whose largest magnitude was 5.8 at September 12, 2016. Before the accident, the earthquakes were considered as a different story for Korea that had not experienced such large earthquakes that harm the society and economy. However, the earthquake has suddenly come and alarmed again Korea about the safety issues of nuclear power plants located nearby epicentres.

## 1.2 Literature review

The aggregate production has been steadily increasing over the last centuries in almost countries of the world. GDP per capita of the world increased from USD 449.6 in 1960 to USD 10,004.9 in 2015 with its average growth rate of 1.88% (World Bank, 2015). The recent knowledge-based economy along with a rapid growth in information and communication technology in 21st century demands a faster creation and more use of knowledge than other competitors to survive in the fierce market. Therefore, R&D activities that create knowledge and induce future innovation are highly encouraged and many countries try to increase their budget onto the R&D activities to find new ideas for promoting technical progress, which would shift current structures of technology and industry and ultimately influence on economic growth and national wealth (Yoo, 2004)

### 1.2.1 Concept of innovation

A role of invention or innovation has been being discussed widely over the centuries and it is generally agreed that they are playing a significant role in creating the wealth of society (Smith, 1776; Rae, 1834; Mill, 1859/1929; Schumpeter, 1954). In the classical economies, Adam Smith and David Ricardo explained that capital accumulation as well as technical progress are considered significant factors for the economic growth. Then, the theory of economic growth has been stylized and described by the two large growth models; exogenous and endogenous growth models.

The exogenous growth model in the perspective of macroeconomic is advanced by Ramsey (1928) and Solow (1956), looking the long-term and stable economic growth is determined exogenously; technical shock or technical change are given as a result of innovation without any compensation. On the contrary, in a more recent endogenous growth model, the economic growth is realized based on accumulated knowledge and human capital (Romer, 1986; Lucas, 1988). In other words, various activities concerning creation and production of new knowledge, representatively R&D activity, are significant and essential for the economic growth.

Schumpeter, who advanced one of the most impressed thoughts on innovation, describes the process of 'creative destruction' as an essential function of capitalism, in which innovation creates something original and new and destroys something existed and old and with luck the worth of creation will surpass the worth of destruction (Schumpeter, 1954). He insists that the incessant process of 'creative destruction' is performed much more effectively in the competition than the function of price that is a traditional idea developed by neoclassical economics.

The process to trigger innovation proceeds largely three stages according to Schumpeterian trilogy: invention, innovation and diffusion stages. New idea is discovered, collected, created and accumulated at the invention stage and some inventions are designed and developed as marketable products or processes at the innovation stage in sequence. Then, the new innovative products and processes are spread out in the potential market at the diffusion stage, and the rate of diffusion varies by level and type of technologies and countries. This technology driven linear model of innovation is depicted in Figure 1.10.

The invention is considered as new idea, which may be made by accident; for example, the discoveries of plastic, nylon, rubber, or microwaves or by activities on research and development (R&D) and other types of creativity. The recent invention is mostly made through the latter process that requires a lengthy period and a financial investment in labour force and technological device that are normally pricey.

R&D is defined as creative and systematic works to increase the stock of knowledge and devise new application of available knowledge according to the Frascati Manual published by the Organization for Economic Cooperation and Development (OECD) (OECD, 2015). The activities of R&D can be largely divided into basic, applied, and experimental development researches according to the expected use of the results. Basic research is performed to obtain new knowledge of the fundamental findings of phenomena and observable reality without any expectation of application and use in order. Applied research is carried out to acquire new knowledge to accomplish specific and practical aims or objectives. Last, experimental development is to draw new or additional knowledge from the applied researches in order to produce new products or processes or to improve existing products or processes. Therefore, the development research is much nearer to the market than the basic research.

However, while the investments for R&D activity in the invention stage is significant, which helps to accumulate and absorb knowledge from the new idea in external sources, it is not always indispensable for the source of innovation. Therefore, R&D performers, especially in the private firms, tend to invest on products or processes that have higher potential to gain commercial value sufficiently high to be sold in the potential market. Consequently, they are also looking for a way to protect and prevent the invention passing through a long process of R&D efforts from being easily comped by the rivals: patents, registered designs, trademarks and copyright as a formal intellectual property protection or secrecy as an informal protection (Swann, 2009).

The characteristics of R&D investment are listed as non-specificity, time lag, uncertainty, and costliness (Kay, 1988). Non-specificity means that the results of R&D investment created are diffused throughout the economy, not limiting to a specific agent, product, or process. In addition, there is frequently time lag in that it takes generally long time and much expense to create certain forms of result from the R&D investment; for instance, direct outputs of research papers or patent or economic outcomes through innovative product or processes. Moreover, uncertainty denotes that the positive result of R&D investment is not always followed; research failure, not expected result, none of economic compensation from the R&D investment would also take place.

Only few inventions that are successfully designed and developed to acknowledge their commercial value in the market can be called finally as an innovation. Innovation is defined in many ways: “an idea, practice, or object that is perceived as new by an individual or other unit of adoption” by Roger (2003) or “the successful exploitation of new ideas” by Swann (2013). Newness in innovation is subjectively perceived by its


Figure 1.10. The simplistic linear model of innovation

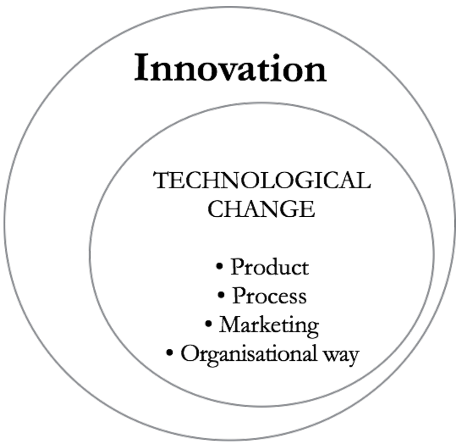



Figure 1.11. A scope of innovation and technological change

adopter, which means that innovation should not be always created with new knowledge. If an idea looks like unknown and new to someone, it can be called as an innovation.

In addition, technological change, which is another term to be distinguished from the innovation, is a part of innovation as depicted in Figure 1.11. (Stoneman, 1995/2002; Rogers, 2003; Swann, 2013). The innovations that contains new technology that has not been discovered or used earlier can generate technological changes in innovation of product, process, material and intermediate inputs, marketing or management ways.

In this context, the issues about how to diffuse the successful innovation in a society and how to accelerate the rate of its diffusion are naturally concerned. Roger (1995) defines the diffusion of innovation as "*the process by which an innovation is communicated through certain channels over time among the members of a social system*". He says that the diffusion of innovation is a special type of communication interested in a new idea and may alter the structure and function of a social system. Due to uncertainty inherent in a 'newness' of innovation, an activity to gather information is carried out to reduce the uncertainty about the innovation. Then, only few innovations that succeed information seeking is selected to adopt and diffuse among the members of a social system.

Each innovation shows the different rates of adoption, and the characteristics of relative advantage and compatibility in innovation are crucial to differentiate the newly introduced innovation from the existing idea that is expected to replace with the innovation (Rogers, 2003). The innovation is occasionally perceived relatively advantageous than the idea substituted. Relative advantage may have a higher chance to be adopted, and the rate of diffusion may faster as the perceived relative advantages are greater. In addition, the innovation's degree compatible with the existing values, past experience and needs of potential adopters, that is, compatibility determines the rate of diffusion of newly adopted innovation.

However, it is arguable that the complicated process of innovation and its diffusion that leads and determine the rate and direction of innovation or the wealth creation can be simply described on a straight line as well as does not flow in one-direction from invention to diffusion. The multiple kinds of interactions and certain forms of feedbacks can be generated between any other steps of innovation processes and influence across the whole processes. Moreover, the innovation can be driven from demand-side of future users and create opportunities for firms to invest more in safe innovative activities that will bring more predictable profits (Griliches, 1957; Rosenberg, 1969).

### 1.2.2 Consequence of increasing use of fossil fuel and risks from energy security

The energy sector has been heavily dependent on fossil fuels that include petroleum oil, natural gas and coal since the “Industrial Revolution” in the 18th century. Although its share in the global energy supply has slightly decreased from 1980 levels, the fossil fuels maintain nearly a line of 80% of total energy consumption during the last five decades, as shown in Figure 1.12 (IEA, 2015). Consequently, the climate has suffered from GHGs that are emitted from the increasing use of fossil fuels, disturb the atmosphere and confuse the earth’s temperature control system. In 2007, the Intergovernmental Panel on Climate Change (IPCC) reported that the global average temperature is already 0.7 ℃ above the pre-industrial level and anticipated to increase 0.5 ℃ more as a result of the thermal inertia of the earth’s temperature system owing to mainly carbon dioxide ($CO_2$) released from the fossil fuel consumption and the land use change.

The large responsibility for the excessive emission of $CO_2$ that is considered as a main culprit of climate change may lie in industrialized countries. Measured on a thermal equivalent basis as shown in Figure 1.13, the member countries of the Organization for Economic Co-operation and Development (OECD) consumed 5,323 million toe in 2013, which accounts for 39.2% of the world’s energy use and the main energy sources for the countries came from 4,309 million toe of fossil fuels that include coal, oil and gas. In addition, it is noticeable to see the recent sharp increase in energy demand in the economic growth within countries such as Brazil, Russia, India, and China (hereinafter BRICs countries). These emerging economies continue to require more energy as their economy grows and, not surprisingly, the GHGs will be much more released from these countries.

While most so-called advanced countries enjoy economic prosperity and social stability, small island countries vulnerable to climate change, are reported to slowly sink with a particular consequence of sea level rise. During the past century from 1910 to 2010, the rate of global sea level rise was 1.7 mm per year and its average rate from 1993 to 2010 was surprisingly shown accelerated much more sharply, presenting at 3.2 mm per year. The melted glacier owing to increasing use of fossil fuels could displace

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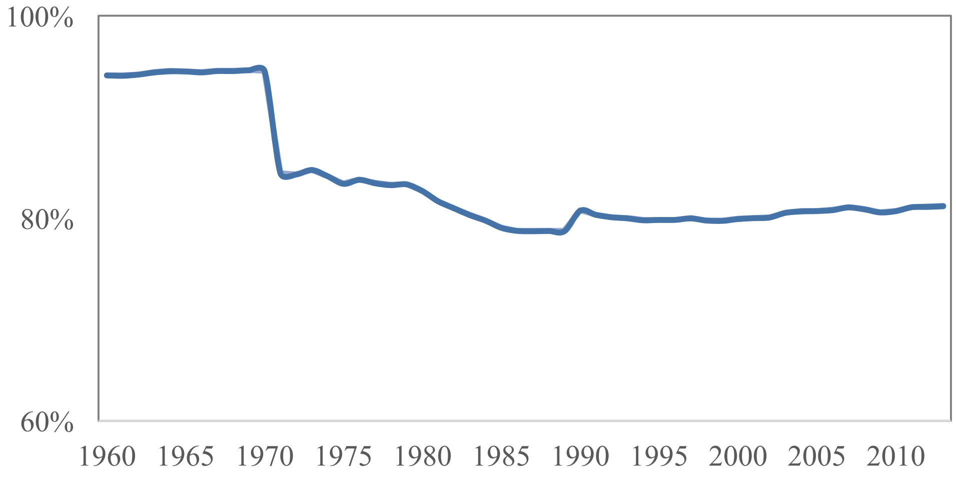



Source: IEA (2015)

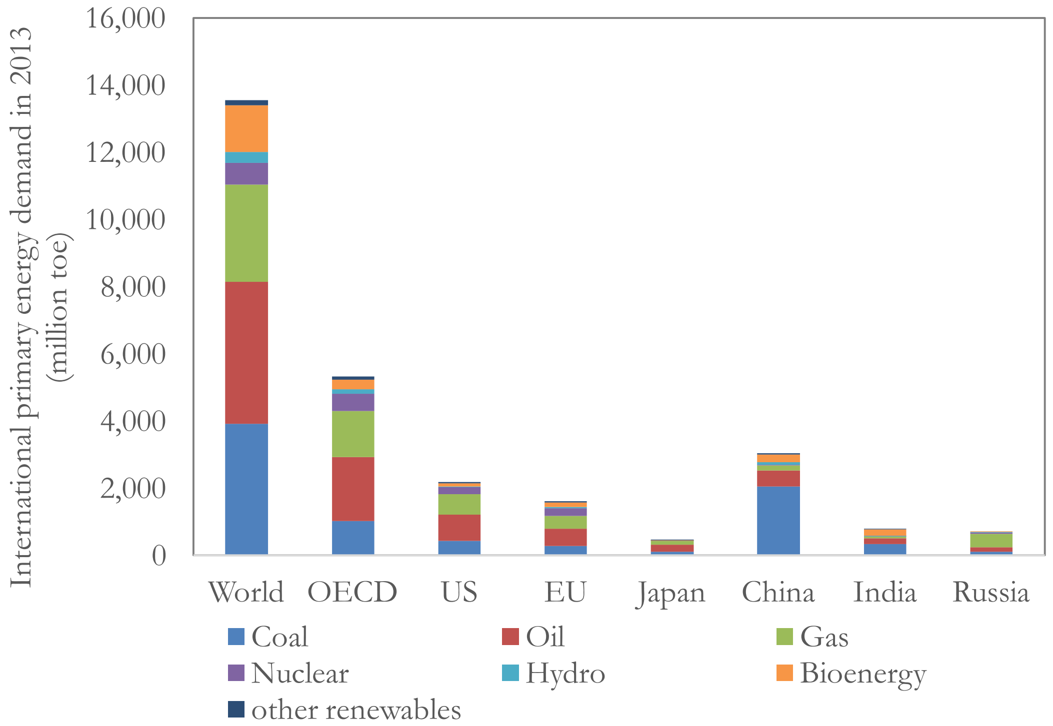
Figure 1.12. International fossil fuel energy consumption

tens of millions of people living in the low lands. In addition, the wildlife is seriously at risk of extinction at present due to the various threats caused by the abnormal climate change that give rise to excessive number of floods, drought, and fire.

The fossil fuel reserves are limited in few countries such as Middle East countries, the United States, Russia, and Canada. Therefore, their volatile price and high supply risks are threating other countries that are highly dependent on the imported the fossil fuels. As shown in Figure 1.14. describing the oil price (based on Dubai crude oil), the price shows a rising trend until 2008 and sharply decreases in 2009 due to the international financial crises largely caused by the subprime mortgage crisis in the United States (IMF, 2016). The oil price has fallen again in recent years since 2014 and the main reasons to be told are the economic recession in Europe, China and Japan and the shale gas production in the United States. However, the price is certainly to rise again because the fossil fuels are finite, which will be depleted one day and will not meet the demand that keeps increasing along with the economic growth, particularly like in BRICs countries.

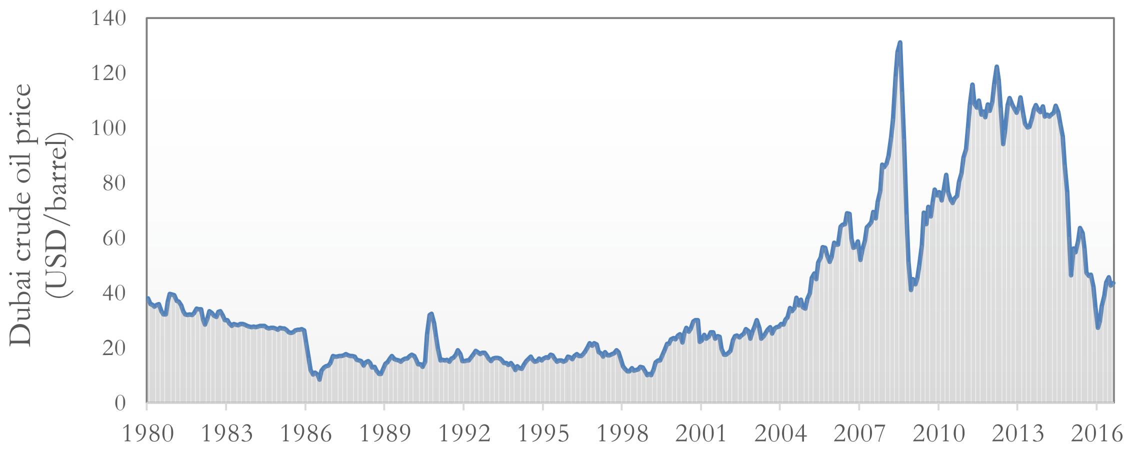
Various efforts have been made to face challenges to energy security since the earlier energy crises occurred in 1973-4 when the oil prices dramatically rose almost five-fold during that period. The economy of industrialized countries, which had taken advantage of using cheap oil since the Second World War, was seriously shocked by the oil crises and began to take political actions in regards to high dependency on finite fossil fuel reserved largely in some limited countries in the Middle East. In addition, some countries have changed their energy mixes; for example, France has transformed their energy balance with a large construction of nuclear power plants by powerful state-owned electricity company under a strong national commitment to economic planning. On the other hand, Denmark has selected a more decentralized energy sector by local authorities to install combined heat and power (CHP) and district heating networks in most urban areas as well as notably renewable energy (Scrase et al., 2009).

While the previous oil crises in 1970s were caused by the soared oil price by conflicts in the Middle East and the substantial united power of OPEC, the next oil crises can be anticipated by the “Peak Oil” that the global conventional oil will imminently peak, subsequently decline sharply in reserve and consequently increase the oil price again according to the laws of supply and demand. It is a point of debate when the oil




Source: IEA (2015)

Figure 1.13. International primary energy demand by regions in 2013




Source: IMF (2016)

Figure 1.14. Dubai crude oil price from 1980 to 2016

production will be depleted[3], but it is irrefutable and observable phenomenon that the fossil fuels as finite resources will exhaust the reserves unless we stop consuming it. Therefore, it is significant to increase use in alternative energies that can realize to reduce imports of the fossil fuels and true energy independence for the greater national security and the stable economic growth.

### 1.2.3 Previous studies on R&D activities in renewable energy technology

In Korea, active debates and studies on R&D activities are currently being held at national level as the efficiency of R&D productivity has been much more emphasized recently in a condition that R&D investment increases year by year. To enhance the efficiency of R&D productivity, thorough ex-ante and ex-post analysis and assessment on R&D projects are strongly demanded to avoid unnecessary use of governmental funding and time at the needless research. In addition, while government departments or agencies are performing the current management system of R&D projects separately, it is recommended to unify the separated systems into one R&D evaluation system to control and facilitate outcomes of R&D projects easier and efficiently. Furthermore, a role of National Science & Technology Information Service (NTIS) that established in 2007 to give information on R&D projects from a stage of planning to the practical use of R&D results in order to improve R&D efficiency should be strengthened. In the future, it is expected that NTIS performs as a significant bridge to provide R&D participants with useful and fruitful information so that the result of R&D can link to technological transfer or commercialization.

In the energy sectors, studies on R&D productivity is heavily performed particularly in the renewables while studies on R&D activities in fossil fuels and nuclear power are mainly carried out in regards to simple descriptions of current national or international circumstances since they are already playing a significant role as energy sources in Korea. Korea still has a lower performance in R&D investment in renewable energy technology compared to other OECD countries under the condition that GDP per capita is excluded due to R&D increasing as GDP increases (Min & Kang, 2014). It seems that return on R&D is becoming more visible in sales and export along with recent R&D

[3] The estimate on oil reserve is inherently uncertain due to a limited share of its information hold by few private companies and Organization of Petroleum Exporting Countries (OPEC) that may may distort the figures (Scrase, Wang, MacKerron, McGowan, & Sorrell, 2009).

increases, especially in PV and wind energy technology; however, the technologies are not yet sufficient to compete in the international market, and the requisite R&D has been lacking, partly due to a lack of national R&D support (Jin & Im, 2007).

In renewable technologies, despite extensive efforts in R&D since 2008 to catch up with advanced technology, the level of commercialization derived from technology supported by Korean R&D activity and export of domestic goods (that is considerably important for Korea whose domestic renewable energy market was only 0.5 % of the global market in 2011) are in sluggish. This is largely due to the lack of core technology needed to lead in the international market. The Korean market share in the international renewable energy technology was 0.27% in 2012, increased slightly compared to 0.18% in 2008 (Kang & Oh, 2013). Sales in renewables were KRW 3,268 billion in 2008 and increased to KRW 7,515 in 2013; exports were USD 1,706 million in 2008 and increased to USD 4,770 million in 2011; this trend then entered a downturn, with USD 2,523 million in 2012.

R&D productivity in selectively concentrated R&D investment on large firms that conduct systematic researches mostly on development phase in order to achieve a short-term diffusion goal may slow development in core technology development on components, equipment, and materials in which smaller firms are interested (MOTIE, 2012). For instance, the industrial import dependency in the PV module, a core component for PV, is highly dependent on import (46.6% in 2008) because of the lack of reliability, the shortage of skill, low price competitiveness, and so on (MOTIE, 2012). Moreover, the import dependency in wind energy power plant installed in the country was 99.6% in 2008, since the generating firms prefer the foreign product due to the low technological competitiveness in supporting core components and materials in charge of domestic smaller firms (Park H. , 2013).

Chang (2010) shows that Korea industrial R&D programs of government tends to show higher performance in universities than firms and research institutes in terms of number of paper publication and patent registration and in venture firms than medium-sized firms in terms of patent registration. In addition, the R&D performance would improve with industry-academic cooperation and the ratio of investment from private firms is larger.

In addition, Kim et al. (2009) uses the Dynamic Computable General Equilibrium (CGE) of emprical model to analyze and assess if renewable energy and green car has a possibility to grow as one of representative so-called green technology that is a technology to reduce or not to emit Greenhouse gases (GHGs). The study proposes to develop the green technology from a long-term perspective until increasing GDP and Green car is likely relatively to grow faster than renewable energy technology.

Jin and Im (2011) utilizes 1,451 data of firms that receive support of Feed-in Tarff (FIT) as of 2010 to estimate an effect on production and employment inducement in terms of industrialization. Consequently, renewable energy industry has a large ripple effect in respect of production inducement but not employment inducement related to job creation and improvement in unemployment. Analyzed by energy sources, both production and employment inducement is high in case of wind energy but not photovoltaic called as a "Korean second semi-conductor".

As results of quantitative research, the extended R&D support in renewable energy technology would be desirable in Korea to increase GDP (Kim et al., 2011). The efficiencies of renewable energy R&D in terms of paper, patent, and engineering fee increased yearly as well as being shown to be comparatively more efficient than other energy programs such as nuclear energy (Choi et al. 2014). By energy source, wind power is shown to be the most efficient in terms of the government support including R&D and promotion compared to other renewables such as fuel cells and PV (Kim et al. 2014).

On the other hand, it has been also shown that if renewable energy R&D performance described representatively as paper and patent are relative to the economic value, stability, profitability, growth, and innovation in firms who received R&D support to spend for renewable energy technology are not increased significantly compared to the firms that did not receive R&D support. This indicates that R&D support in renewable energies is not being connected to the firms' performance by technical commercialization (Oh & Lee, 2014).

Oh and Jeong (2015) carry out a quantitative analysis on Korean renewable energy firms that have received national R&D supports to see the invested programs creates economic value through technological commercialisation. Propensity Score Matching (PSM) that is possible to solve a problem of selection bias is used as an analysis model. As a result, the firms supported by R&D investment do not increase much sales or assets compared to the none-supported firms, which means the performed R&D supports is little likely to lead the firms economic performance through the technological commercilization.

The results of research may be interpreted variously according to analysis methodology and research purpose, but there is no doubt that the aim for R&D activity is to achieve profits in the future. The approach of delivering heavy investment to large firms may need to be reconsidered. As firms grow large, efficiency in R&D is weakened due to the loss of managerial control or excessive bureaucratic control as well as the incentives of individual researchers being weakened owing to decreasing their ability to capture the benefits from their individual efforts or conservative characteristics of the hierarchies of large firms that may frustrate their creativity (Galbraith, 1952).

On the other hand, there are distinctive benefits that favour the large firms over the smaller firms (Scherer & Ross, 1990). For instance, the large firms are able to conduct risky R&D in an imperfect capital market by utilizing their internally generated funds, which are more available and stable as firms grow and provide economies of scale to reduce the risk associated with the prospective return from R&D activity. In addition, there are economies of scale in R&D activity and the returns from R&D are higher in firms that have a larger volume of sales that can be used to spread out the fixed cost generated during R&D activity.

The concept of productivity is naturally valid in the renewable energy technology that is regarded to be significant as a future growth engine for Korea, and it is important to assess and enhance the R&D productivity in a qualitative way beyond quantitative growth. However, there have been no empirical studies to estimate Korea R&D productivity in renewable energy technology by performers (larger and smaller firms as well as institutes and universities) that are playing an essential role in conducting public R&D activity as well as by technical phases (basic, applied and development) whose purpose to perform are dissimilar one another.

## 1.3 Research aims and questions

As shown in Figure 1.14 that describes drivers of innovation in renewable energy technology in Korea, it is obvious that the renewable energy technology should be developed to deal with challenges presented previously of energy security as a country that limits the fossil fuel reserves and climate change as a country that is responsible for a large amount of GHGs emissions. In addition, the innovation in new renewable technology will the future industry for the long-term and stable economic growth as well as solve the problems of high unemployment rate that Korea is facing with.

This research attempts to analyse Korea R&D investment of renewable energy technologies, whose effectiveness is still in doubt compared to the recent bold R&D effort. Therefore, it is required to evaluate productivity of R&D investment in Korea renewable energy technology, separating R&D performers and technological phases whose characteristics and purposes of carrying out R&D activities vary. In addition, assumed the accumulated knowledge by the R&D activity is significant for innovation, one type of renewable energy technology who receives largest R&D support is selected to forecast its future price considering R&D investment. Here, the study chooses PV technology to estimate its future price and examines the energy will reach its target price stated in the 2nd National Basic Plan for Energy" by 2035 and have an ability to compete conventional energy sources in the market.

The research purposes are as in the following, (1) to understand a role and impact of R&D activity in the process of innovation and its diffusion, (2) to analyse Korea political instruments including R&D policy in renewable energy technology and compare them with relevant policies in other major countries that have advanced renewable energy, (3) estimate a productivity of national renewable energy R&D by performers and technological phases, (4) forecast the future price of PV technology considering R&D impact, and (5) to suggest policy implications to deliver innovation in renewable energy more effectively.

The specific research questions to answer in this research are (1) Is there a tendency of the productivity of R&D increases as the size of firm is larger? and (2) Will the PV price reach the target price by 2035 and have an ability to compete other energy sources in the market?

## 1.4 Research design

First of all, Korean current status in terms of energy production and political and legal instruments relevant to renewable energy technology will be chronologically described. The application and target of "National Basic Plan for Energy" and "Basic plan for the promotion of the development, use and diffusion of new and renewable energy" for renewable energy is indicated. The R&D as well as other diffusion policies including Feed-in Tariff (FIT) and Renewable Portfolio Standards (RPS) are explained.

Characteristics of Korean R&D programs are specified by renewable energy sources and indicate its purpose to perform in price reduction. Last, measurement and procedure of post evaluation on performed R&D are presented. Current circumstances in some other major countries that have advanced technology in renewable energies are also described and compare them with Korean status.

To analyse Korean R&D productivity in renewables, the Schumpeter's hypothesis is adopted which reads, "There is a positive relationship between innovative activity and firm size". Based on this hypothesis, the R&D productivity is measured by performers of large firms and medium-sized firms as well as research institutes and universities. The R&D activity is separated by technological phases of basic, applied, and development researches due to their varying purpose in implementation.

The methodology used for the analysis is an empirical tool called "Data Envelopment Analysis (DEA)". The tool enables to measure productive efficiency using non-parametric way with multiple inputs and multiple outputs generated in R&D activities. The input considered are R&D investment and number of labours and the outputs are divided into direct outputs of number of publication, patents and others and economical outputs of number of receiving engineering fee and commercialization.

The PV technology is selected to estimate its future generation price to see if the energy will reach a target price and be competitive with other energy sources by 2035. Most of all, the Korean PV module price is forecasted by using 2 Factor Learning curves (2FLC) that takes into account cumulative capacity and accumulated knowledge measured by past R&D investment. Subsequently with the PV module price, the future PV generation price is estimated by Levelised Cost of Electricity (LCOE) by 2035.

The effectiveness of R&D activity into renewables in Korea is examined by productivity and future price measured with R&D investment in researches above. After reviewing its strengths and weakness in practice and compare its achievement with other major countries, the policy implication and suggestions are to draw for future development in Korean renewable energy technology.

## 1.5 Outlines

A structure of the dissertation is described in the Figure 1.15. Chapter 2 as following chapter will describe the current legal and political interventions as well as R&D

activities towards renewable energy technology in Korea. Chapter 3 carries out efficiency analysis of R&D productivity by Data Envelopment Analysis (DEA) and Chapter 4 deals with the future Photovoltaic (PV) price, considering impact of R&D. Finally, Chapter 5 will describe conclusion of the dissertation.

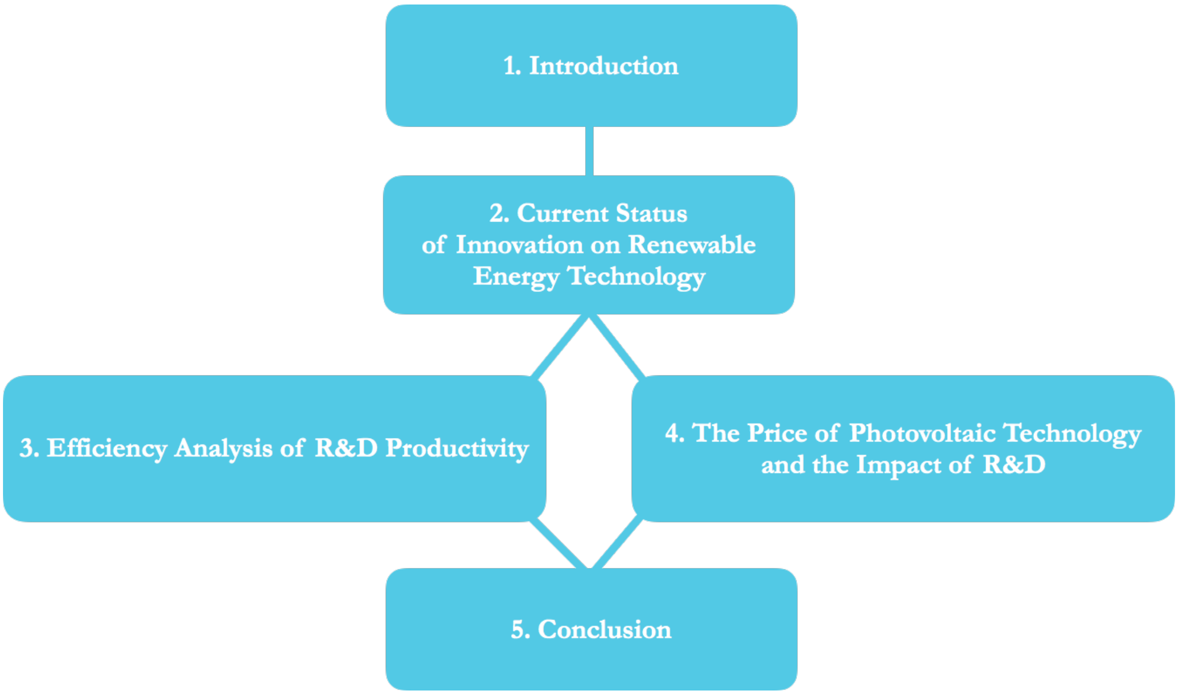



Figure 1.15 Structure of the dissertation

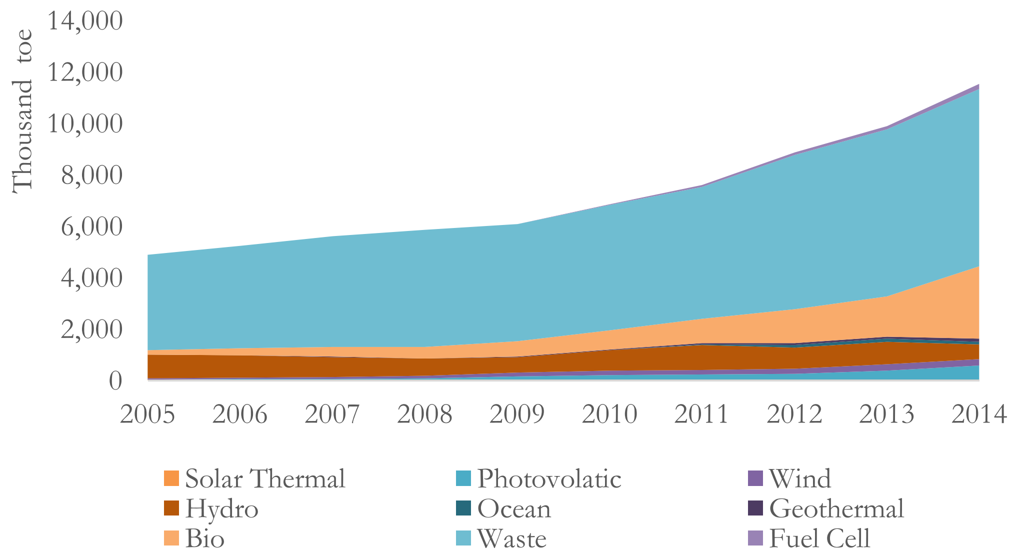
# 2 Current Status of Innovation on Renewable Energy Technology

## 2.1 Introduction

A policy of support for renewable energies was firstly introduced in the “Alternative Energy Development Promotion Act” in 1987 in light of concerns over Korea’s energy security as a country that depends highly on imported fossil fuels and various environmental problems occurred due to climate change. The support has been strengthened as of the “2nd Act on the Promotion of Development, Use and Diffusion of New energy and Renewable Energy” implemented in 2003. This occurred again in 2008, when “Low Carbon and Green Growth” was proclaimed as the nation’s vision to lead development during the next 50 years and the “National Strategy for Green Growth” was announced to mitigate climate change, create new engines for economic growth, and improve the quality of life.

The term “new energy and renewable energy” (hereinafter referred to as “new and renewable energy”) means energy resources converted from existing fossil fuel resources or renewable energy sources, including the sun, water, geothermal heat, precipitation, and bio-organisms, which fall under any of the following items: (a) Solar energy; (b) Bio energy converted from biological resources, which falls within the criteria and range prescribed by Presidential Decree; (c) Wind power; (d) Water power; (e) Fuel cells; (f) Energy from liquefied or gasified coal, and from gasified heavy residual oil, which falls within the criteria and scope prescribed by Presidential Decree; (g) Energy from the ocean; (h) Energy from waste treatment, which falls within the criteria and scope prescribed by Presidential Decree; (i) Geothermal energy; (j) Hydrogenous energy; and (k) Sources of energy prescribed by Presidential Decree, other than petroleum, coal, nuclear power, or natural gas.

The new and renewable energy support policies are classified largely into research and development (R&D), diffusion, and industry promotion. As shown in Figure 2.1. below, the Korean new and renewable energy production in 2014 is 11,537 thousand toe (KESIS, 2016), and is likely to grow continuously in the future. The waste energy, bio energy, and hydro power dominates the new and renewable energy production and PV, wind energy, and fuel cell are predicted to play a significant role as a clean energy source within the nation’s energy mix in the near future.




Source: KESIS (2016)

Figure 2.1. Korea renewable energy production by sources

## 2.2 Legal and political interventions

Major events in the history of Korean legal and political instruments in renewable technology are listed in Table 2.1. Active R&D program on new and renewable energy technology in Korea was started in 1987 with the first legal effort into technological development in renewables of "Alternative Energy Technology Promotion Act", recognizing a need of stable energy supply as a long term perspective after experiencing oil crises in 1970s. Eight renewable energies (photovoltaic, solar-thermal, wind energy, bioenergy [including combustible renewables], ocean energy, geothermal, hydropower, and wastes [including industrial waste]) and three new energies (fuel cell, hydrogen, and integrated gasification combined cycle (IGCC) are specified to promote under the present "Act on the Promotion of Development, Use and Diffusion of New and Renewable Energy".

The "Basic Plan for the Promotion of the Development, Use and Diffusion of New and Renewable Energy" is established every 10 years, based "Act on the Promotion of the Development, Use and Diffusion of Alternative Energy". "1st Basic Plan for the Promotion of the Development, Use and Diffusion of New and Renewable Energy (1997~2006)" was established for the sake of the technological development in the new and renewable energy. The plan aims at producing new and renewable energy to 2% of TPES by 2006, selecting the solar thermal, photovoltaic, fuel cell, and IGCC that are highly expected to be competitive with ones' technological level of advanced countries as four major programs.

"2nd Basic Plan for the Promotion of the Development, Use and Diffusion of New and Renewable Energy (2003~2012)" was established in 2003 and the new production target by new and renewable energy was determined at 5% of TPES by 2011. While the first plan focuses on the technological development in the new and renewable energies, the second plan is meaningful to include the efforts for its technological development as well as diffusion.

The hydrogen and fuel cell, wind energy and photovoltaic whose technological level is close to the level of advanced country and market potential is bigger than other renewables are selected as major programs to focus and those developed technologies are to connect to the diffusion program. Solar thermal, bio energy and waste energies whose market is already being formed are focused for the diffusion in parallel with those technological developments.

In the interests of diffusing new and renewable energy, a role of government to invest mandatorily 5% of total construction cost for renewable energy is addressed to widen the market to attract active and large private demands of the renewable energy. The local government's diffusion program of new and renewable energy adequate to its natural environment or fiscal circumstances is also encouraged; for instance, wind power farms were built in several districts like islands, coastal line or mountainous region where the wind is plentiful such as the wind generation farm in Jeju islands.

The standardization and certification of new and renewable energy facility is another diffusion policy. Feed-in tariff (FIT) introduced in 2012 is a financially support instrument for diffusion of new and renewable energy, aiding a differences between System Marginal Price (SMP) that is a hourly generation cost from the power plants and established standard price of new and renewable energy. The generation by photovoltaic, wind power, small hydraulic power, tidal power, landfill gas, and waste are initially applied for the FIT.

"3rd Basic Plan for the Promotion of the Development, Use and Diffusion of New and Renewable Energy (2009~2030)" is established with a background that the green energy industry is announced to perform as one of future growth engines in pursuit of 'Low Carbon, Green Growth' as a nation's vision for the next decade and four industries out of nine are new and renewable fields, which are PV, wind power, hydrogen and fuel cells and IGCC. The "3rd National Energy Basic Plan" that is upper national energy plan aims at increasing a supply by new and renewable energy at 11% of TPES by 2030 as a quantitative target and industrializing the new and renewable energy technology of new growth engine as a qualitative target.

The new and renewable energies are largely divided into two groups: one includes wind energy, bio energy, waste energy, geothermal energy that are technologically matured and needed to focus on diffusion process, and the others such as PV, hydrogen and fuel cells that should concentrate on R&D activity to largely contribute the diffusion objective in the near future. The major diffusion programs are "One Million Green Homes" by 2020 providing systems of of PV, solar thermal, geothermal and wind energies to the one million homes and the government procurement of renewable energy technologies in their public building. The Renewable Portfolio Standards (RPS) is substituted with FIT in 2012, who imposes certain amount of generations from new and renewable energy in their energy supply on some large power plants and the mandatory.

Table 2.1. History of major legal and political instrument for new and renewable energy in Korea

| Year | Major policy instruments | Main contents |
|---|---|---|
| 1987 | Enactment and proclamation of "Alternative Energy Technology Promotion Act" | Legal basis to R&D activities and supports to alternative energy |
| 1997 | Amendment of "Alternative Energy Development Promotion Act" to "Act on the Promotion of the Development, Use and Diffusion of Alternative Energy" and "1st Basic Plan for the Promotion of the Development, Use and Diffusion of New and Renewable Energy (1997~2006)" | Supporting renewable energy deployment and forming an institution on the energy<br>Increasing a supply by new and renewable energy at 2% of TPES by 2006 |
| 2002 | Amendment of "Act on the Promotion of the Development, Use And Diffusion of Alternative Energy" | Duty on alternative energy use to public buildings, qualifying facilities, FIT, and concept of sustainability |
| 2003 | "2nd Basic Plan for the Promotion of the Development, Use and Diffusion of New and Renewable Energy (2003~2012)" | Building a 10-year plan for supply target, plan on strategy and action, and technology roadmap<br>Increasing a supply by new and renewable energy at 5% of TPES by 2011 |
| 2004 | Amendment of "Act on the Promotion of The Development, Use and Diffusion of Alternative Energy" To "Act on The Promotion of The Development, Use and Diffusion of New and Renewable Energy" | Technology product standardization, and adding a strengthen provision on management supports |
| 2008 | "3rd Basic Plan for the Promotion of the Development, Use and Diffusion of New and Renewable Energy (2009~2030)" | Revising supply target and basic strategy on industrialization acceleration<br>Increasing a supply by new and renewable energy at 11% of TPES by 2030 |
| 2009<br>2010 | Amendment of "Act on the Promotion of the Development, Use and Diffusion of New and Renewable Energy" | RPS introduction, and use duty on new public building |
| 2014 | "4th Basic Plan for the Promotion of the Development, Use and Diffusion of New and Renewable Energy (2014~2035)" | Relating to "2nd National Basic Plan for Energy", expanding renewable energy supply and export industrialization<br>Increasing a supply by new and renewable energy at 11% of TPES by 2035 |

Table 2.2. Share of new and renewable energy on the basis of primary energy supply

| | 2012 | 2014 | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|---|---|
| Share of new and renewable energy | 3.2% | 3.6% | 5.0% | 7.7% | 9.7% | 11% |

Source: Fourth Basic Plan for the Promotion of the Development, Use and Diffusion of New and Renewable Energy (2014-2035)

Table 2.3. Target share (%) on the basis of primary energy supply from new and renewable energies

| | 2012 | 2014 | 2020 | 2025 | 2030 | 2035 | Annual average growth rate (%) |
|---|---|---|---|---|---|---|---|
| Solar thermal | 0.3 | 0.5 | 1.4 | 3.7 | 5.6 | 7.9 | 21.2 |
| Photovoltaic | 2.7 | 4.9 | 11.7 | 12.9 | 13.7 | 14.1 | 11.7 |
| Wind energy | 2.2 | 2.6 | 6.3 | 15.6 | 18.7 | 18.2 | 16.5 |
| Bio energy | 15.2 | 13.3 | 18.8 | 19.0 | 18.5 | 18.0 | 7.7 |
| Hydro power | 9.3 | 9.7 | 6.6 | 4.1 | 3.3 | 2.9 | 0.3 |
| Geothermal energy | 0.7 | 0.9 | 2.7 | 4.4 | 6.4 | 8.5 | 18.0 |
| Ocean energy | 1.1 | 1.1 | 2.5 | 1.6 | 1.4 | 1.3 | 6.7 |
| Waste energy | 68.4 | 67.0 | 49.8 | 38.8 | 32.4 | 29.2 | 2.0 |

4th Basic Plan for the Promotion of the Development, Use and Diffusion of New and Renewable Energy (2014~2035) rate of new and renewable energy is increased annually and finally reaches at 10% in 2020. The most recent "4th Basic Plan for the Promotion of the Development, Use and Diffusion of New and Renewable Energy (2014~2035)" was announced in September 2014 and is aiming at increasing the use of renewable energies to 11% of TPES. There are 6 main projects in "4$^{th}$ Basic plan for the promotion of the development, use and diffusion of new and renewable energy", which are (1)Policy enforcement on demand-side diffusion, (2)Market friendly system management, (3)Overseas market expansion in new and renewable energy, (4)New market creation in new and renewable energy, (5)Reinforcement of R&D capability in new and renewable energy and (6)Expansion of institutional support.

As mentioned earlier, Korea is aiming at producing 11% of renewable energy on TPES by 2035 with 6.2% of average annual growth rate, described in Table 2.2. PV and wind energy will substitute the waste energy that currently accounts for the largest portion in the new and renewable energy production. The specific target shares on the basis of TPES by energy sources until 2035 are shown in Table 2.3. As the shares of waste energy decreases, solar energies of PV and solar thermal are anticipated to increase by 22% and wind energy and bio energy are following with target shares of 18.2% and 18.0% respectively.

## 2.3 R&D programs

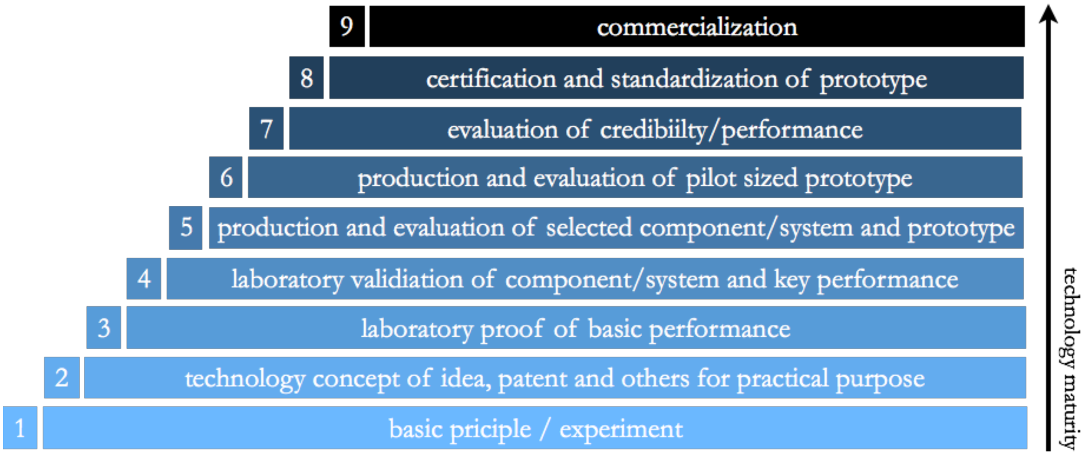
R&D programs in new and renewable energy are to carry out according to Technology Readiness Level (TRL) since 2010, as depicted in Table 2.4. and Figure 2.2. below. The research tasks are divided into two categories: short-term programs focused on core technologies close to a step of commercialization and mid- and long-term programs for acquiring future core technologies and cultivating manpower coupled with professionals training. The short-term programs are performed to develop practical technology for price reduction in generation, commercialization, demonstration, diffusion policy connected type, and others, which are utilized for the early diffusion.

Objectives of the mid-and long-term R&D programs lay in to develop the future leading technology, which is expected to industrialized within 10 years especially. The technologies that would be included for mid- and long-term R&D are PV, fuel cell, bio energy and very large floating offshore wind technology, and the convergence technology that is the hybrid system connecting the generation systems of new and renewable energy with Energy Storage System (ESS). It is significant to cultivate

Table 2.4. Definitions according to R&D task types

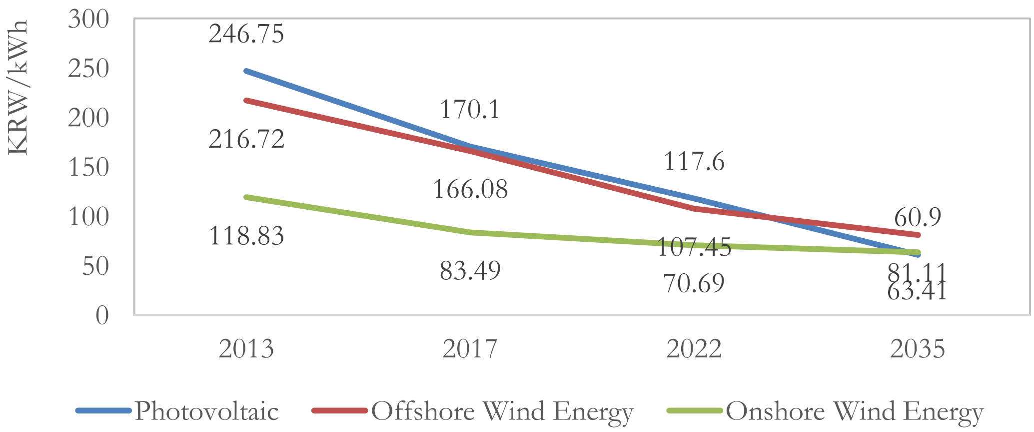
| Period | Task type | Period (year) | Task outline | TRL |
|---|---|---|---|---|
| Mid- and long-term | Core technology | ~5 | Beneficiaries; Industry, university and institute<br>Purpose; Acquiring patent of core technology<br>Size; Annually approx. KRW 1 billion<br>Technological scope; future technology with new and innovative substitution effect<br>*in case of previous studies needed, annually KRW 0.3 billion within 3 years | 2~4 |
| | Strategical applied technology | 3~5 | Beneficiaries; Industry, university and institute<br>Purpose; Acquiring patent of applied technology and production of prototype<br>Size; Annually approx. KRW 1~3 billion<br>Technological scope; Creating peripheral technologies by applying core technology<br>*exception of support period and size according to characteristics by projects | 4~5 |
| | Commercialized technology (prototype) | ~3 | Beneficiaries; Industry<br>Purpose; Acquiring patent of commercialized technology<br>Size; Changeable according to size of projects<br>Technological scope; commercialized technology after completing R&D (e.g. experiment of process and demonstration)<br>*the size of support is decided in regard with preliminary feasibility survey | 6~7 |
| Short-term | Key technology | 2~3 | Support beneficiaries; Industry<br>Purpose; Acquiring technology of applied and commercialized technologies<br>Size; annually approx. KRW 0.5 billion<br>Technology scope; the technology with common problems that should be solved urgently | 5~7 |

KETEP (2014)




KETEP (2014)

Figure 2.2. Definition of 9steps of Technology Readiness Level (TRL)



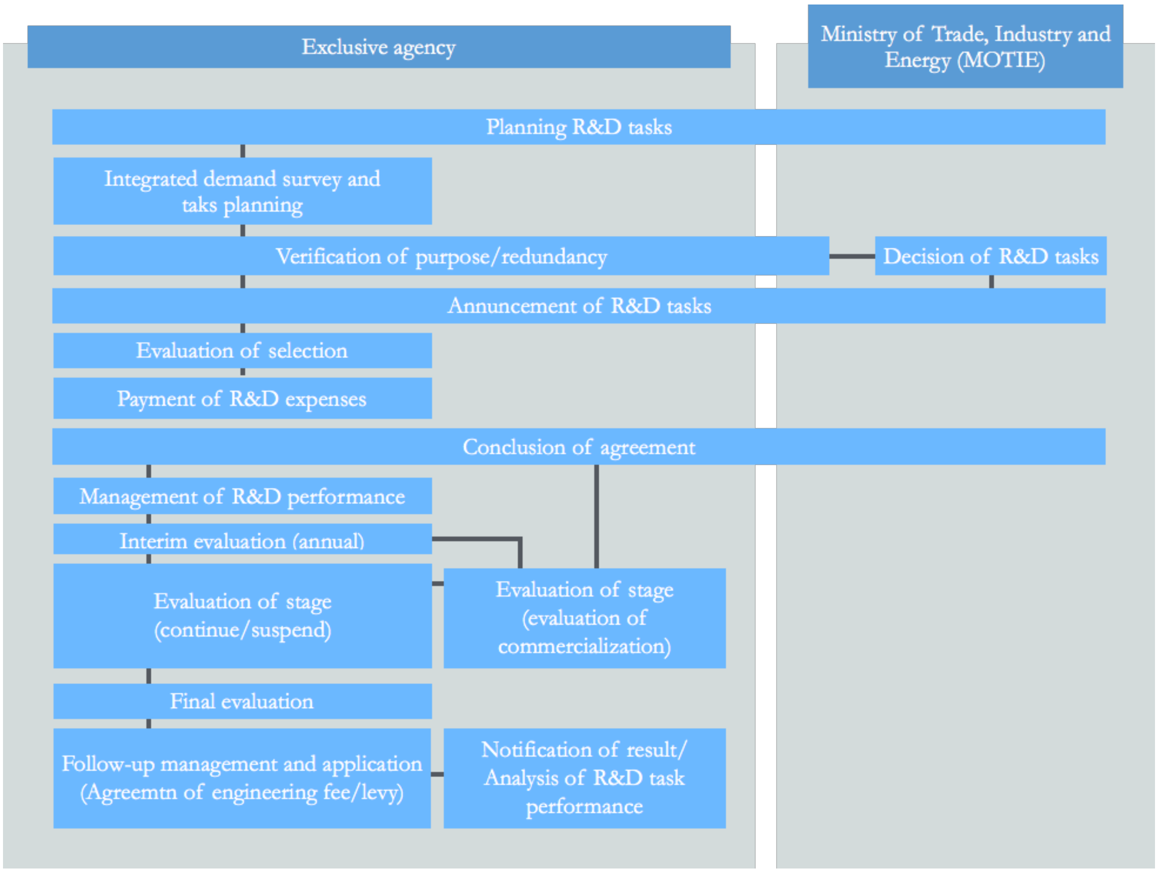

Fourth Basic Plan for the Promotion of the Development, Use and Diffusion of New and Renewable Energy (2014-2035)

Figure 2.3 Scenario of price reduction in generation by sources manpower for the renewable energy technology in connection with professionals training and job creation especially in the medium-sized firms for supporting their technological competitiveness.

The export-led R&D projects specified for the local circumstance can be also supported in the whole processes of production from the technology development to commercialization. Demonstration R&D for Building Integrated Photo Voltaic (BIPV), offshore wind energy, integrated coal-gasification combined-cycle power system (IGCC) and other technologies should be enlarged to obtain the credibility including life spans and quality for the export industry and rapid accumulation of track record of the technology is able to lead the new market in advance. Moreover, the R&D projects needed for the diffusion policy and technology that is possible to use promptly in the market are encouraged to support to the system of connecting the technology to the diffusion step.

The scenario of price reduction in generation by sources, in terms of KRW/kWh, is shown in Figure 2.3., which is able to enter the market without problems through the minimization in investment cost with the technology road map capable of reaching the expected reduction price. Support for commercialisation includes the technological supports to promote the developed technology to use in the whole life cycle of production for smooth commercialization like process technology, package, automation, and equipment technology for mass production, reliability verification and others.

The government establishes annually the plan for renewable energy R&D, accepts R&D tasks through project information, evaluates and chooses R&D tasks, and finally supports R&D tasks selected. The precise process of R&D is described below in Figure 2.4. After the conclusion of agreement between exclusive agency, Ministry of Trade, Industry and Energy (MOTIE), and R&D beneficiaries for the R&D tasks, thrice evaluations are to perform, annual interim evaluation for the projects longer than one-year, evaluations of stages to decide continuing or suspending R&D tasks and verify whether the tasks is to commercialize or not, and final evaluation.




KETEP (2015)

Figure 2.4. Process of Korean Renewable energy R&D program

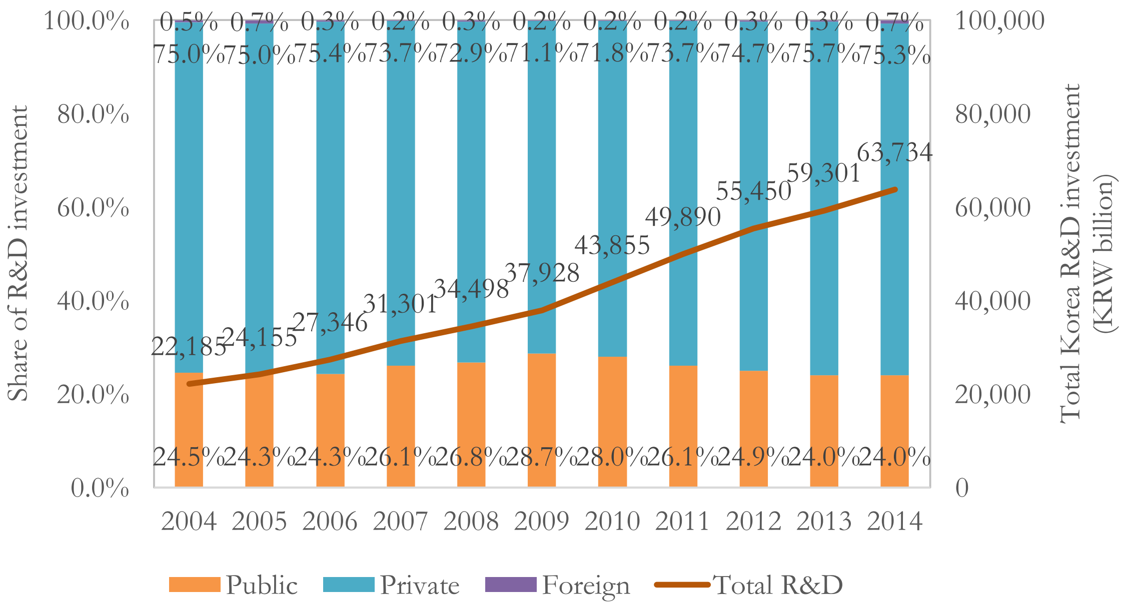
## 2.4 R&D investment

In Korea, financial support for R&D activities in renewables has been provided since 1988, and approximately 10% of total public R&D is annually used for developing technologies in renewable energy and nuclear power as new energy sources to counteract climate change and reduction in GHGs. The total R&D investment in renewable energy technology until 2013 is KRW 3.71 trillion, which increased especially sharply in the last decade from 2004 to 2013 at a 25% average annual growth rate (KETEP, 2014). The public R&D support in 2010 and 2011 accounted for 6.07% and 4.92% respectively out of IEA countries' renewable energy R&D expenditure (OECD/IEA, 2014). However, despite the recent bold renewable energy R&D investment policy, the past-accumulated investment during the last few decades is regarded as far behind those of other technologically advanced countries like the United States, Germany, France, Japan, and the United Kingdom.

The innovation is important for Korea that has limited natural resources to exploit in its narrow land and high-educated human resources, and the country's innovative industries to lead market are believed to be a key factor to survive in the competitive world. Accordingly, the second five-year economic development plan was implemented in 1967 and the Ministry of Science-Technology was established as one of government organizations, and R&D investment was regularized for the first time. The amount of R&D investment in 1967 is KRW 4.8 billion and increased by KRW 100 billion after one decade in 1977 (Yoo, 2004).

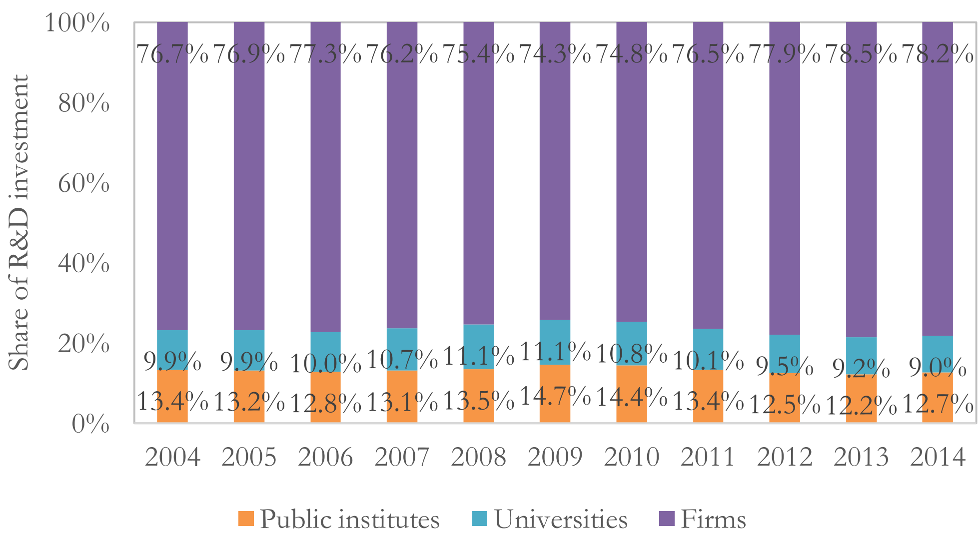
Korean R&D investment has continued to increase as shown in Figure 2.5. below (OECD, 2015). The R&D investment in 2014 is KRW 63,734 billion in total and 4.292% as a percentage of GDP, which is the highest share of the year among OECD countries (OECD, 2016; National Science & Technology Council, 2015). The private R&D investment is KRW 48,008 billion, holding the largest share of 75.3% as a percentage of total and public and foreign R&D are estimated as KRW 15,275 billion (24%) and KRW 450 billion (0.7%) respectively. Public R&D is comparatively lower than other key countries; for example, 37% of France in 2012, 34.7% of the United States in 2013, 32.8% of the United Kingdom in 2013, 30.1% of Germany in 2013, and 21.1% of China in 2013.

A trend in Korea R&D investment by performers is shown in Figure 2.6. KRW 49,855 billion in 2014 is used for Firms' R&D that accounts for 78.2% of total R&D




Source: KISTEP (2015)

Figure 2.5. A trend in Korea R&D investment by sources




Source: KISTEP (2015)

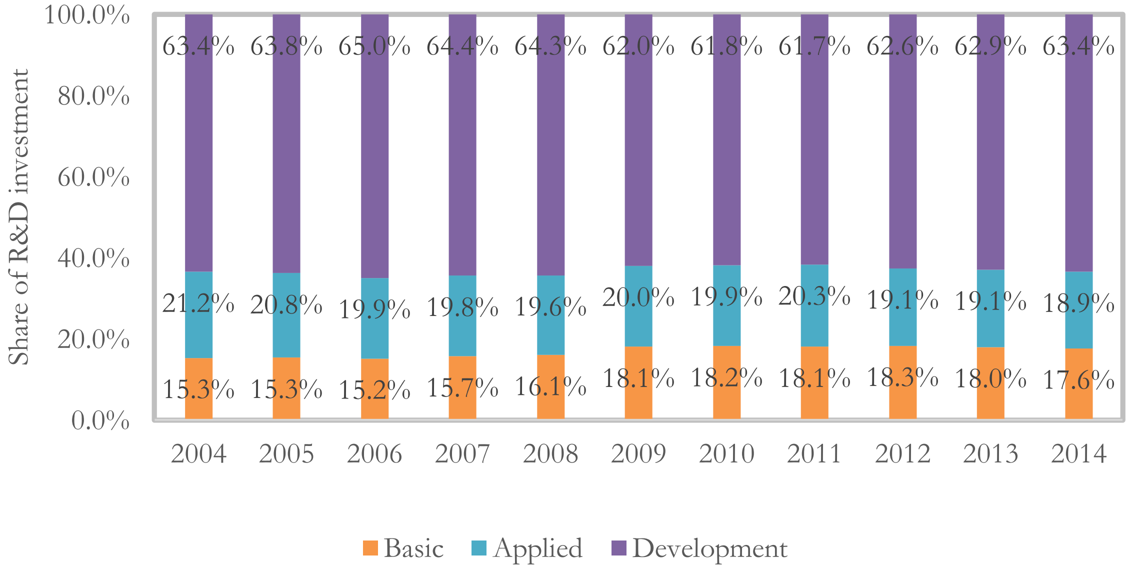
Figure 2.6. A trend in Korea R&D investment by performers

investment. Compared to the share of firms' R&D to other key countries, Israel is the only country that has larger share than Korea; 84.4% in 2014, and other key OECD countries show smaller shares than Korea: Japan (77.8%), Germany (67.5%), the United Kingdom (64.4%), and the United States (70.6% in 2013). The share of government and public institutes as performer in R&D investment is 12.7% and other countries show Japan (9.64), Germany (14.8%), the United Kingdom (9.51%), the United States (15.3% in 2013), and China (15.8%) (OECD, 2015). On the other hands, the share of R&D investment flown to universities is 9.0% that is considered to be lower than other OECD countries; for example, Japan (12.6%), Germany (17.7%), France (20.6%), the United Kingdom (26.1%), and the United States (14.2% in 2013) (OECD, 2015).

Figure 2.7. shows a trend in R&D investment by technological phases and the investment in development research is KRW 40,433 billion in 2014, followed by KRW 12,585 billion in applied research and KRW 11,243 billion in basic research. The investment in basic research as a percentage of GDP, Korea shows relatively higher than other OECD countries, 0.75% in 2013, followed by Japan (0.44%), France (0.54%), the United States (0.48%), and China (0.09%).

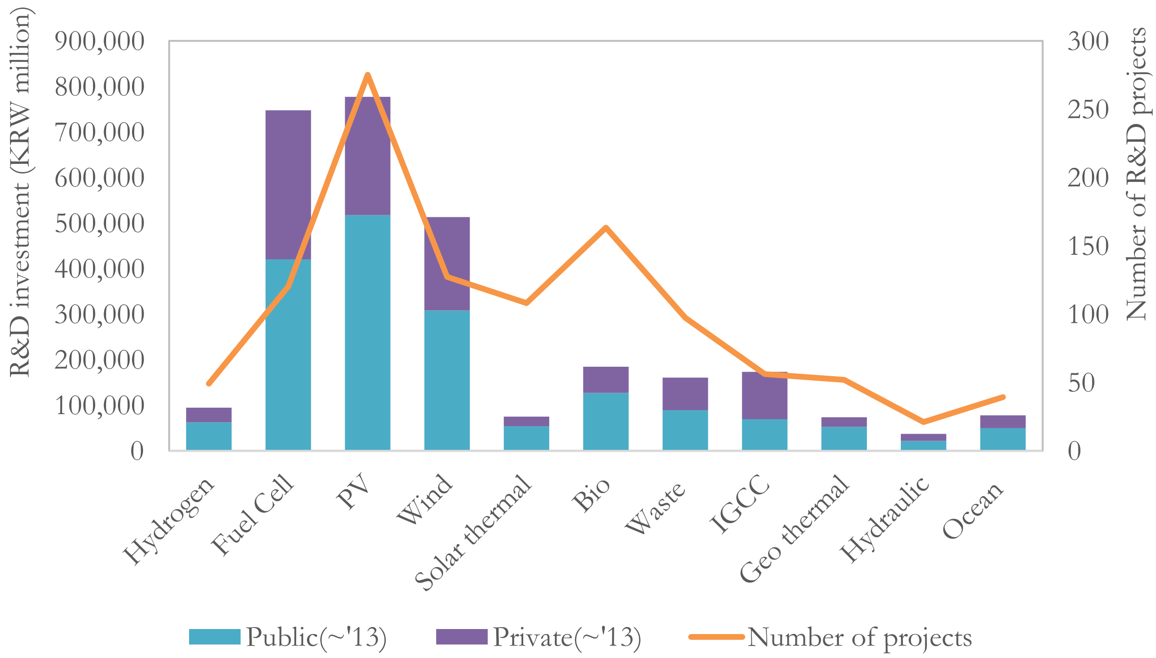
Figure 2.8. shows a R&D trend in new and renewable energy by sources (NTIS, 2014). The R&D tasks are strategically divided into short-term tasks for technologies with potential to be commercialized in the near future and medium- and long-term tasks performed in order to acquire future core technology. In the short-term tasks, the pragmatic technologies, like photovoltaic (PV), wind energy, and fuel cell, which can be utilized for current early diffusion by lowering electricity generation cost, supporting commercialization and overseas market expansion, and linking R&D with diffusion policy, are subjected preferentially to a heavy investment. PV received the most R&D investment among the eleven renewable energies both in number of projects and in amount of financial investment: 275 projects accounting for KRW 777.2 billion in R&D investment for new and continuous projects. Fuel cell and wind power are the next, representing 120 and 127 new projects, respectively, and KRW 747.38 billion and KRW 513.36 billion, respectively, in R&D investment for new and continuous projects. These three energies, which are designated as priority supporting energies, account for 54.95% of total renewable R&D investment.

While public R&D investment in new and renewable energy has decreased in recent years, with KRW 277,304 million in 2012, KRW 271,963 million in 2013, and KRW




Source: KISTEP (2015)

Figure 2.7 A trend in R&D investment by technological phases




Source: NTIS (2014)

Figure 2.8. Korean R&D trend in new and renewable energy by sources by 2013

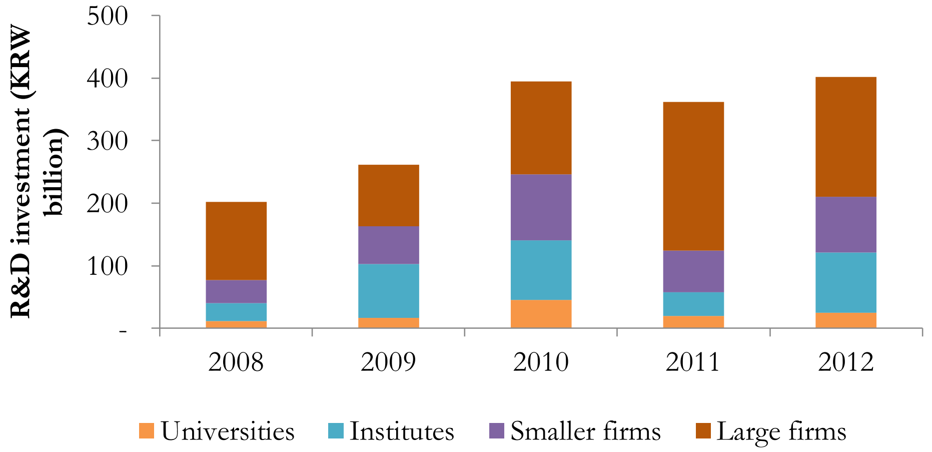
249,305 million in 2014 (Chae, 2014), the investment trend in terms of average amount per project is getting larger, and considerable R&D investment is still being delivered into large firms whose research is mainly large in finance and on the development phase that can generate economical profits in the short term and focus on a system field that includes activities such as standardization, planning, demonstration, operation, performance evaluation, and so on.

Figure 2.9. shows a trend in R&D investment from 2008–2012 by performers, and the large firms are taking the most advantage of R&D investment among beneficiaries, representing nearly half of the R&D of KRW 243,223.38 (54.01%) from 2008 to 2012, while others like smaller firms, institutes, and universities received KRW 147,461.80 (32.75%), KRW 43,313.50 (9.62%), and KRW 16,311.64 (3.62%) respectively during the same period (NTIS, 2014)[6].By technological progress phases as shown in Figure 2.10., 759 new and continuous R&D projects took place on development phase, which accounts for nearly 70% of total R&D projects, gaining the most financial support, of KRW 556,431.7 billion, between 2008–2012 (NTIS, 2014). The research on the development phase was mostly carried out by large and smaller firms and basic and applied researches by universities and institutes.

It is significant for Korea to switch its current energy mix that is dependent on imported energies to a more sustainable energy mix and to continue to develop renewable energy technology in order to strengthen the competitiveness in overseas market for energy security and economic development as well as environment protection. The nation has been making much political and financial effort in its diffusion by FIT and RPS that is one of major diffusion political instrument as well as its technology development by R&D activities from basic to development researches.

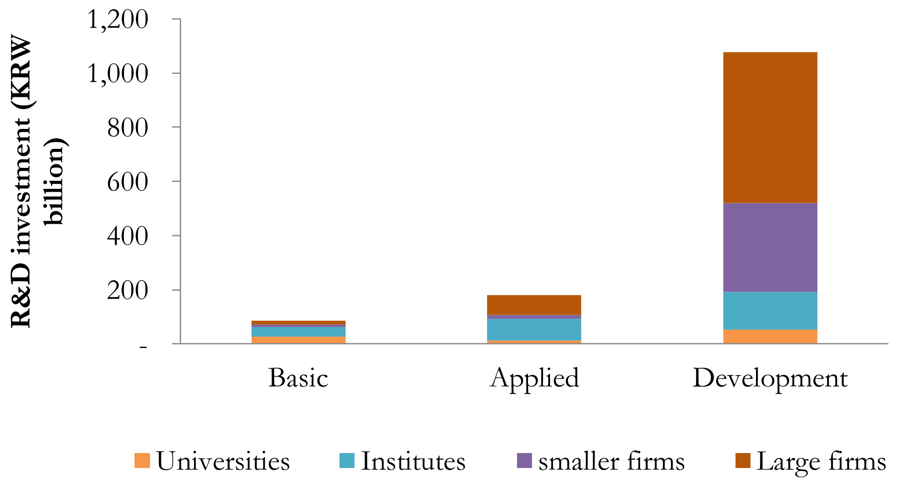
However, Korea is having trouble both in domestic and overseas markets in use of its renewable energy technologies. The conventional fossil fuels and nuclear power are still major energy sources for the country and the share of renewable energy in TPES is close to 4% in 2016, low as ever. It is showing a good economic achievement at export

[6] Here, the criteria classifying larger and smaller is based on "smaller enterprises basic law." The term "large firms" applies to several conditions: that number of full-time labor is more than 1,000, the equity capital is over KRW 100 billion, or average sales are more than KRW 150 until 2014. The law was revised in 2015 with new revised applications, for instance the firms whose 3-year average sales is suited to the criteria by type of industry, total amount of assets is less than KRW 500 billion, and who do not belong to the firm group of limited mutual investment are defined as smaller firms.




Source: NTIS (2014)

Figure 2.9. Renewable energy R&D support by performers phase from 2008-2012




Source: NTIS (2014)

Figure 2.10. Renewable energy R&D support by technological progress phases from 2008-2012

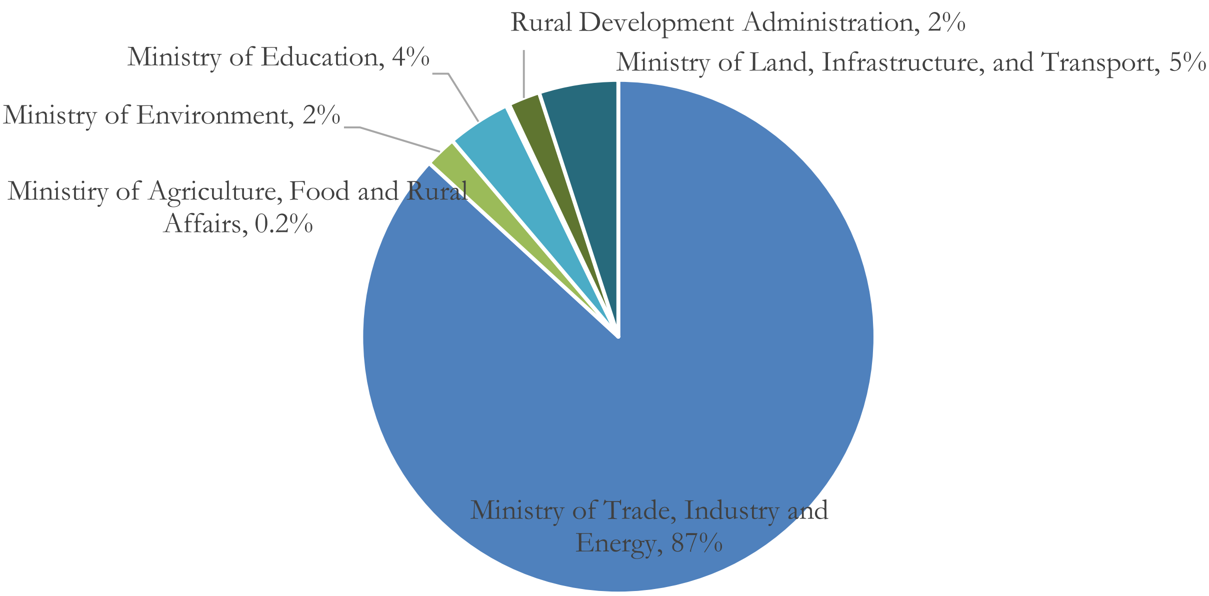
of polysilicon industry that one supply chain in photovoltaic technology but does not have evidently a good progress in other technologies in the overseas market. In addition, it is an energy dependent country; 99% of fossil fuels are imported from abroad, but its key industries are mostly manufacturing industry that are heavily consuming energy; for example, vehicle, shipbuilding, steel, semiconductor, and petrochemical. Therefore, they prefer to use cheap energy sources and the price of renewable energy is not satisfying them now.

## 2.5 Conclusion

Korean support for renewable energies is essential as a country that depends highly on imported fossil fuels, consumes energy intensively due to its energy-guzzling key industries, and emit GHGs that lead to environmental problems and climate change. The first legal effort to battle a series of matters was shown in 1987 and eventually "Low Carbon and Green Growth" was proclaimed as the nation's vision in 2008. "4th Basic Plan for the Promotion of the Development, Use and Diffusion of New and Renewable Energy (2014-2035)" has been implemented since 2014 and the plan is aiming at increasing the use of renewable energies to 11% of TPES. The production by renewables is estimated nearly 4% as a percentage of TPES in 2016 and it is vital to increase the production faster to correspond to the national vision.

The technological development in new and renewable energy demands Korea to decrease its price to compete with the existing traditional energy sources as well as contributes as a stable source to the energy market. In addition, its technological development will enhance its competitiveness in the market that continues to grow and become a significant source of sales in the near future. The scale of Korean R&D investment for renewables has been increasing since the late 1980s and increased by KRW 63,734 billion in 2014 that accounts for 4.3% as a percentage of GDP and presents the highest percentage of the year within OECD countries.

The Korean renewable energy support policies are consisted of "Research and Development (R&D)", "Diffusion", and "Industry promotion" and it is crucial to categorize the renewables according to the level of technological development. For instance, some kinds of PV and wind energy, which indeed occupy the large shares in sales among renewables, should be selected to assist for the phase of diffusion or industry promotion. However, the most of renewable are still in the infant stage technologically and needs more political and financial supports for their advancement




National Science and Technology Commission (2012)

Figure 2.11. R&D investment in renewables by governmental departments in 2011

up to the moment when they can contribute to the national energy supply system as one of stable and continuous sources.

Different kinds of energy are considered as renewable in different countries. There is no internationally unified definition for renewables and each country can define the energy as renewable energy according to its energy reserve or environmental condition. Korea promotes energies mentioned as new and renewable energy that are not contained within coal, petroleum, nuclear, and natural gas and are environmentally friendly and sustainable infinite energy that do not emit $CO_2$. While IEA classifies ten types of energy as renewables, which are waterpower, geothermal, PV, solar thermal, ocean power, wind power, solid biomass, biofuel, biogas, and renewable wastes. Korean "New and Renewable Energy" are eight renewables of solar energy divided by PV and solar thermal, bio-energy, wind power, water power, ocean energy, waste energy, geothermal energy and three new energies of fuel cell, hydrogen, and IGCC.

However, the Korean classification that includes all kinds of biomass as well as waste energy including industrial wastes is much broader than other international criteria. It could impede the genuine sustainable renewable's development since these eleven energies are counted together into the national energy production goal to reach by renewables. In addition, one of the largest arguments for the slow development in renewables is generally stated as the reserve of renewables but the recent studies show that the price of PV has attained the grid parity and its reserve would be much larger than the present statistics measured, which can provide a basis for competing against traditional energy sources of fossil fuels and nuclear power.

The frequently changing policy on renewables is also considered one significant factor to hamper renewables' development. The key diffusion policy of RPS has changed its mandatory rate once in every two year since implemented in 2012, and the national production goal by renewables has been changed every time when "Basic Plan for the Promotion of the Development, Use and Diffusion of New and Renewable Energy" is revised. The target share of renewable energy was at 2% as a percentage of TPES by 2006 in the "1st Basic Plan for the Promotion of the Development, Use and Diffusion of New and Renewable Energy (1997~2006)" and was changed at 5% by 2011 in the $2^{nd}$ basic plan, 11% by 2030 in the 3nd basic plan, and finally 11% by 2035 in the current $4^{th}$ plan. Particularly, renewables' technology on the introductory period needs a consistent and long-sighted policy establishment for performers to anticipate the future.

In 2011, the R&D investment in renewables is KRW 458 billion, which accounts for 37.5% among five different energy sources of nuclear, coal, LNG, crude oil and renewable energy ( National Science and Technology Commission, 2012). The pubic R&D activity in renewables is performed by six governmental departments of Ministry of Trade, Industry and Energy (MOTIE), Ministry of Agriculture, Food and Rural Affairs (MAFRA), Ministry of Environment (ME), Ministry of Education (MOE), Rural Development Administration (RDA), and Ministry of Land, Infrastructure, and Transport (MOLIT). As shown in Figure 2.11., the major departments for renewables' R&D activity is MOTIE whose R&D investment is granted in large scale and in various forms in the most of renewable technologies. While the R&D activity is being carried out various performers, it is crucial to investigate thoroughly if the same research has been already performed in the different departments of the government. The active cooperation between the departments is critical to avoid the duplicate researches that would waste time and budget and furthermore slow the technology development.

In addition, the performed R&D should not ignore follow-up management to link its result to the activities to generate economic achievement. While the R&D investment in renewables continues to grow, the outcomes of economic performance led by the accomplished R&D projects has shown weak and insufficient. The efficiency of R&D productivity in renewable technology should be reinforced and improved to catch up with the advanced technology faster and dominate the market in advance.

The following chapter will handle the efficiency of R&D productivity within the renewable technology by performers in Korea because the country has been traditionally highly depending on a small number of large firms and, therefore, the large scale of R&D investment has granted those large firms. The next chapter will analyse the R&D in PV technology because it is one of most advance renewable technology among eleven new and renewable energies and granted the largest scale of R&D investment in the country. The study will find out how large the R&D activity has influenced on PV technology and predict the future price of Korean PV technology with a consideration of R&D impact.

# 3 sEfficiency Analysis of R&D Productivity

## 3.1 Introduction

In Korea, where 4.29% of GDP was used for R&D activity in 2014, an issue on high efficiency of R&D productivity has been widely discussed in depth. The R&D productivity is empirically estimated by a ratio from inputs presented as R&D investment, human resources, time and other commitments necessary for R&D activity to outcomes delivered as diverse forms of paper, patent, revenue, and others. An ultimate role of R&D is said to create and accumulate new knowledge that is capable to substitute the past and old notion, but it finally can gain a high recognition when providing economic benefits to agents that have invested onto the R&D activities. Therefore, innovative technologies or performers that are likely to result in high sales performance expectable in the near future show a propensity to be offered more R&D investment.

The country has been traditionally highly depending on a small number of large firms; for instance, globally also renowned Samsung, Hyundai and LG that have brought a rapid and significant economic growth to the nation since 1970s. They have actively been investing in their own R&D projects to lead a market faster than other competitors have and been large beneficiaries of pubic R&D investment. The R&D investment spent by firms in 2014 is estimated at KRW 49, 855 billion that is 78.2% of total R&D and R&D budgets to governmental research institutes and universities of the same year are KRW 8,113 billion and KRW 5,767 billion (National Science & Technology Council, 2015).

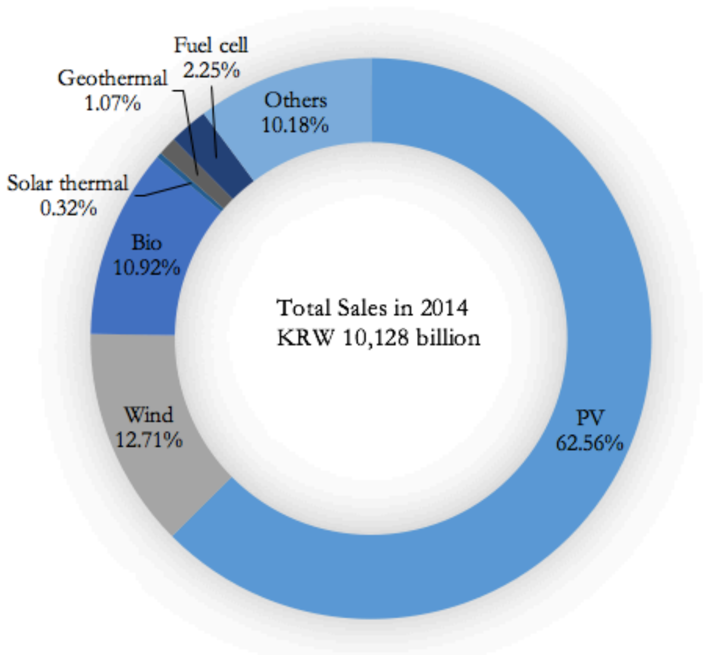
Subdividing the firm's R&D investment in 2014, the large firms' R&D investment is KRW 38,638 billion that occupied 77.5% as percentage of the firm's R&D investment. On the other hand, the R&D investment for three million smaller firms with 1.2 million workers is only KRW 5, 947 billion (11.9%). Simultaneously, the largest share in renewable energy R&D investment is flowing to the large firms whose total amount of R&D investment from 2008 to 2012 is KRW 243,223 billion that accounts for 54.01% of total firm's R&D investment (NTIS, 2014). R&D investments for smaller firms, institutes, and universities during the same period are KRW 147,462 billion (32.75%), KRW 43,314 billion (9.62%), and KRW 16,312 billion (3.62%) respectively.

Here, the criteria classifying large and smaller is based on “smaller enterprises basic law”. Large firms applies to several conditions that number of full-time labor is more than 1,000, the equity capital is over KRW 100 billion, or average sales are more than KRW 150 billion until 2014 and the law was revised in 2015 with new revised applications, for instance the firms whose 3-year average sales is suited to the criteria by type of industry, total amount of assets is less than KRW 500 billion, and who is not belong to the firm group of limited mutual investment are subject to smaller firms.

While the industrial development of renewable energy in Korea is rather late than other advanced countries, it has showed a rapid growth by means of strong and strategic supports from the government. The sales renewable energy technology sharply increased from KRW 3, 268 billion in 2008 to KRW 10, 128 billion in 2014 (KOTRA, 2015). As Figure 3.1 that depicts the sales by energy sources in 2014 shows, PV technology occupies the largest share of the total renewable sales (62.56%) and wind energy (12.71%), bio energy (10.92%), fuel cells (2.25%) are following. With an increasing sales trend in the renewable energy technology, the investment in the renewables increased by KRW 873.8 billion in 2014 and are likely to keep growing. Large firms such as Samsung SDI, Hyundai mobile, KT, LG Electronics, Hanwha Q CELLS, SK E&S, POSCO ICT and LS IS plan to invest KRW 8,200 billion by 2017 (Lee, 2016).

Korea has a vertical profit creation structure that many smaller firms are playing a role as a subcontracted firm of conglomerates, in which a dominant company can use asymmetric bargaining power and hinder the legitimate profits in the smaller firms. One of the biggest obstacles for smaller firms when dealing with large firms is to be required an excessive decrease in delivery unit price (KIET, 2012). Therefore, the mutual growth in both large and smaller firms has been politicized since the middle of 2000s to settle this problem and the government announced “A countermeasure on the mutual growth in large and smaller firms” to support smaller firms in 2009.

Whereas the need for the mutual growth between firms in the field of renewable industry is also required, the smaller firms in the industry is currently facing with difficulties in sales owing to the large firms that competitively enter and invest the renewable market with their large funding power. Smaller firms have less competitiveness and funding powers to develop their own innovative technology and penetrate the markets that large firms.




Source: KOTRA (2015), KEMPO (2016)

Figure 3.1. 2014 Korean sales in renewable energy technology by sources

In addition, the smaller firms have been harder to join the market that is already limited since the implementation of Renewable Portfolio Standards (RPS) that was substituted with Feed-in tariff in 2012. While RPS has advantages, that it lowers a financial burden for government and is able to easily anticipate the supply from renewables, it also has disadvantages that the investment leans heavily on the renewables that have lower generating price. Thus, the participation of smaller firms in the renewable market is currently more difficult than the time when FIT instrument financially supported the price of renewables.

In the unique vertical economic structure found in Korea, an active R&D cooperation between large and smaller firms is also suggested in renewable industries that is growing (KIET, 2012). The technological improvement in the process and decreasing price of products manufactured in the smaller firms will facilitate large firms to gain more economic benefits and actualize the mutual growth both in large and smaller firms. Therefore, the high efficiency of R&D productivity in the smaller firms is desirable for strengthening their competitive power, expand the market to enter, and furthermore develop the national economy.

However, the excessive governmental support that focused on large firms is considered as a large obstacle for developing renewable energy technology in smaller firms (KEEI, 2010). While the module-manufacturing price of leading firms is about USD 0.53/W in 2013, the price of smaller firms is estimated at USD 0.8/W (KOTRA, 2015). In addition, some technology developed by the smaller firms fail in industrialization due to limited R&D budget to use for to high cost of demonstration. With concerns described above on a polarization between large and smaller firms across Korean industry and the significance on the efficiency of R&D productivity in the renewable industry, this study will handle the R&D productivity from the inputs to outputs by size of firms within Korean renewable energy technology and propose the policy implication for the industry at the end.

## 3.2 Previous studies

Schumpeter is held to be the first to highlight a fundamental role of technical progress in affecting economic growth and social welfare in his book *Capitalism, Socialism, and Democracy* focusing on structural changes in firm, industry, or nation and their market to increase their R&D efforts for improving long-run economic performance (Schumpeter, 1954). He formulates two hypotheses that there is a positive relationship between innovative activity and firm size and between innovative activity and concentrated market structure. That is, large firms operating in a concentrated market will generate the technological progress that will bring economic development at the end. He argued that the process of creative destruction and innovation competition should replace price competition, which would justify monopolistic or oligopolistic competition.

There are also studies of that counter-argument that the large firms are less favourable in terms of innovation (Nelson et al (1967); Pavitt et al (1987); Scherer et al (1990)). As firms grow large, they may either lose managerial control of or become more bureaucratic toward scientists and technologists who perform R&D. Moreover, the incentives given to the scientist or entrepreneurs may not be explicit, as their ability to capture the benefits of individual efforts weakens or their creativity is frustrated by the conservative hierarchies of large firms.

A number of empirical studies that examine a relationship between R&D and firm size are conducted on individual industries or across industries. Some of these studies are done by regression analysis in which R&D intensity is dependent variable and firm size or other influential factors are independent variables. Others use a cross-sectional analysis restricted to R&D performers and spied in a logged form. The studies all endorse this null hypothesis that a proportionality between R&D and firm size would be correlated in most industries regardless of restricting industry effects (Horowitz, 1962; Hamberg, 1964). However, the studies are subject to the controversy that most of the data used for the regression analysis, especially in the earlier firm-level studies, are non-random and that, with fewer exceptions to study presence or the effects of data selection bias, there would be stronger features other than size in the R&D.

Finally, it is necessary to reconsider the Schumpeterian hypothesis with respect to the current condition that most large firms operate business units in diverse industries. Cohen and Klepper (1996) arranged some empirical studies regarding R&D, innovation, and firm size into four stylized facts, “(1) the likelihood of performing R&D rises with firm size; (2) R&D and firm size are closely and positively related within industries; (3) R&D rises proportionately with firm size in most industries; (4) the number of patents or innovations generated per dollar of R&D declines with firm size” and prove them through R&D cost spreading.

The cost-spreading model is based on the idea that large firms have an advantage of size given that the fixed cost generated by R&D can be spread out over a larger amount of output than in smaller firms and, through this process, the return on R&D will increase along with the level of output. It also implies that the rate of technical progress in an industry depends not only on total R&D investment but also on its market structure, such as that the fewer and cooperative firms engaging in R&D activity reduces chance of duplication in R&D spending.

Moreover, the level of business unit that carries out R&D activity is more relevant in saving expenses than overall size of the firm. R&D size is weaker in the industries where innovations are more saleable or the prospects for rapid growth due to innovation are stronger. However, it also emphasizes a role of smaller firms that have peculiar R&D competence on the diversity of projects that enable them to coexist with large firms.

Korean renewable energy R&D is mainly firm-based, representing 86.76% of R&D investment from 2008 to 2012. In addition, recent R&D investment is concentrated on large firms that occupy more than half of total investment. While smaller firms have some benefits in conducting R&D activity as they would provide R&D performers with more flexible working conditions than beauracratic large firms and incentives by capturing individual's efforts in R&D performance, various studies explain how the large firms are favourable for R&D productivity, as per the cost-spreading model, that expects large firms who perform renewable energy R&D to show higher productivity than smaller ones.

Despite sharp investment in renewables R&D in the large firms in Korea, their performance seems not to be very productive as expected and there is a strong demand that R&D towards smaller firms should be more encourage for future renewables development. There is none of empirical study in regards to the relationships between firm size and their performance in Korea. Therefore, this study will study how efficient in renewables R&D in Korea by R&D performers.

Hypothesis: R&D productivity of firms within Korea renewable energy industry is proportionally relevant to the size of the firms.

## 3.3 Methodology

There are two main approaches to analyse R&D productivity: production function and production frontier. One of representative approaches in production function is Cobb–Douglas specification that focuses on mathematical equations that relate quantities of inputs to quantities of maximum level of outputs. That is, its interest lies in estimating the coefficient of regression equations that explain an average propensity of correlation between inputs and outputs.

On the other hand, production frontier is based on estimating a frontier to measure the distance between the frontier and each observed unit, called decision-making units (DMUs), and compares DMUs to know which one is the most efficient. DMUs on the frontier line are described as the best performer in the reference group and benchmarking units to the less efficient DMUs.

Scholars researching innovation and wealth creation generated by technological push simplify a process from R&D activity to invention, design and development, and innovation as a linear model (Swann, 2009). Research and creativity will generate inventions, which are only ideas without economic value, and then some economically feasible invention will be innovated after going through the design and development process. Therefore, firms investing in R&D activity are aiming at gaining economic profits from the innovation by leading the early market in new products' commercialization. A number of input factors are employed throughout the innovation process in various forms; for instance, scientific and technological knowledge as intangible resources and human resources, and time and salary as tangible resources, to result in desired outputs like research papers, patents, engineering fees, and economic outcomes through commercial use. Outputs can be divided into direct and indirect outputs; the former are created directly from the R&D activity and latter refer to the economic outcome that is the ultimate purpose for R&D activity.

### *Data Envelopment Analysis (DEA)*

DEA is developed as one of nonparametric production frontier methodologies to analyse efficiency for like public projects or non-profit firms that the price information on input or/and output is normally not given or units of measure to be estimated are different or difficult to synthesize as one index. In addition, it allows to handle multiple inputs and multiple outputs generated sporadically throughout the process, namely the methodology is useful for estimating R&D productivity since it owns intrinsically various inputs and output. It assumes a condition of Pareto-Koopman efficiency that a unit's efficiency cannot be increased unless other's efficiency decreases (Koopmansa, 1951).

Farrell (1957) introduced the efficiency analysis using multiple inputs and multiple outputs to measure a firm. This analysis was developed by Charnes, Cooper and Rhodes (1978) who proposed DEA for the first time by presenting input-oriented DEA model on a constant return to scale (CRS); Charnes, Cooper and Rhodes (CCR) model, and by Banker, Charnes and Cooper (1984) who distinguishes technical efficiency (TE) and scale efficiency (SE) because the firms' R&D activity is not possible to operate at optimal scale in practical; Banker, Charnes and Cooper (BCC) model.

According to Golany et al. (1989), DMUs used for DEA analysis should satisfy some homogeneity conditions in order to have the result with economic significance (Golany & Roll, 1989). The conditions are (1) the projects are performed under similar purpose, (2) the DMUs are existing in the homogeneity market, (3) all input and output data are in every DMUs and (4) the data are different each other. In addition, the proper number of DMUs should be existed because it is less plausible that majority of DMUs would be efficient if the number of DMUs are less than the number of input and output variables. There is not a unified standard as to the number of DMU but most of papers use the standard suggested by Fitzsimmons et al. (1994) described as below

$$K \geq 2(N+M). \tag{1}$$

K stands for number of DMU and N and M are the number of variables of input and output data, respectively (Fitzsimmons & Fitzsimmons, 1994).

When $n$ decision-making units (DMUs) are to be evaluated, each $DMU_j (j = 1, \dots, n)$ consumes $m$ inputs $(i = 1,2, \dots, m)$ in order to produce $s$ outputs $(r = 1,2, \dots, s)$. Clearly, $DMU_j (j = 1, \dots, n)$ uses amounts $X_j = x_{ij}$ of inputs ( $i = 1,2, \dots, m \ and \ x_{ij} > 0$) and produces amounts $Y_j = y_{rj}$ of outputs ( $r = 1,2, \dots, s \ and \ y_{rj} > 0$). In addition, there are two properties to ensure a piecewise linear approximation to the efficient frontier and the area dominated by the frontier; convexity and inefficiency. That is, $\sum_{j=1}^{n} \lambda_j x_{ij}$ $(i = 1,2, \dots, m)$ and $\sum_{j=1}^{n} \lambda_j y_{rj}$ $(r = 1,2, \dots, s)$ are possible inputs and outputs attainable by the $DMU_j$, where $\lambda_j (j =$

$1,\dots n)$ are positive scalars and the same outputs can be produced by using more inputs; the same inputs can be used to produce less outputs.

The CRS assumption is suitable when all firms are operating at an optimal scale, but it is not possible in the reality due to external factors like imperfect market condition, government regulation, etc.. Therefore, BCC model based on variable returns to scale (VRS) conditions, which can divide TE and SE simply by adding the convexity constraint; $\lambda_j$=1. The input-oriented model estimates the inputs in each DMU that can be minimized while the outputs are maintained; on the contrary, the output-oriented model finds the outputs in each DMU that can be maximized at the current inputs.

Either input or output oriented DEA model is optionally selectable to use for the analysis for R&D productivity according to its research purpose. Input oriented model is suitable to the case in order to estimate minimum input variables at the current output maintained. In other words, the model is capable to acquire minimum R&D investment or/and human resources retaining current output level like number of patent, paper, or volume of sales. In this paper, the efficiency is estimated based on output-oriented BCC model due to the researches and public opinion that the R&D performance is not sufficient to the current level of R&D investment on the increase and the qualitative improvement in R&D productivity is necessary bringing up maximum outputs under the present R&D support.

The efficiency score of output-oriented DEA based on VRS condition (output-oriented BCC model), $\emptyset^*$, is calculated as below

$$\emptyset^* = max\emptyset \tag{2}$$

subject to

$$\sum_{j=1}^{n} \lambda_j x_{ij} \leq x_{io} \qquad i = 1,2,\dots,m; \tag{3}$$

$$\sum_{j=1}^{n} \lambda_j y_{rj} \geq \emptyset y_{ro} \qquad r = 1,2,\dots,s; \tag{4}$$

$$\sum_{j=1}^{n} \lambda_j = 1 \tag{5}$$

$$\lambda_j \geq 0 \qquad j = 1,2,\dots,n \tag{6}$$

If $\emptyset^* \neq 1$, input and outputs slacks can be expressed as

$$s_i^- = x_{io} - \sum_{j=1}^{n} \lambda_j x_{ij} \qquad i = 1,2,\dots,m; \qquad (7)$$

$$s_r^+ = \sum_{j=1}^{n} \lambda_j y_{ro} - \emptyset^* y_{ro} \qquad r = 1,2,\dots,s. \qquad (8)$$

$DMU_o$ is less efficient not only if $\emptyset^* \neq 1$ but also if $\emptyset^* = 1$ and $s_i^-$ and/or $s_r^+$ are non-zero for all $i$. Then, the input and output slacks are estimated, which make $\emptyset^*$ optimize, are also estimated

$$max \sum_{i=0}^{m} s_i^- + \sum_{r=0}^{s} s_i^- \qquad (9)$$

subject to

$$\sum_{j=1}^{n} \lambda_i x_{ij} + s_i^- = x_{io} \qquad i = 1,2,\dots,m; \qquad (10)$$

$$\sum_{j=1}^{n} \lambda_i x_{rj} - s_r^+ = \emptyset^* y_{ro} \qquad r = 1,2,\dots,s; \qquad (11)$$

$$\sum_{j=1}^{n} \lambda_j = 1 \qquad (12)$$

$$\lambda_j \geq 0 \qquad j = 1,2,\dots,n \qquad (13)$$

Finally, the two-state output-oriented BCC model can be evaluated as

$$max\emptyset + \varepsilon(\sum_{i=1}^{m} s_i^- + \sum_{r=1}^{s} s_r^+) \qquad (14)$$

subject to

$$\sum_{j=1}^{n} \lambda_i x_{ij} + s_i^- = x_{io} \qquad i = 1,2,\dots,m; \qquad (15)$$

$$\sum_{j=1}^{n} \lambda_i x_{rj} - s_r^+ = \emptyset^* y_{ro} \qquad r = 1,2,\dots,s; \qquad (16)$$

$$\sum_{j=1}^{n} \lambda_j = 1 \qquad (17)$$

$$\lambda_j \geq 0 \qquad j = 1,2,\dots,n \qquad (18)$$

Next, the VRS model is able to separate TE and SE which may be calculated as the ratio of TE on the assumption of CRS to TE on the assumption of VRS (Banker, Charnes, and Cooper, 1984). The technical efficiencies on the basis of VRS, $\theta^*$ for the input-oriented model and $\emptyset^*$ for the output-oriented model, are given already by calculations above and the TE under the CRS can be estimated without the convexity constraint; $\lambda_j$=1(Charnes, Cooper, and Rohdes, 1978). Therefore, TE under input-oriented based on CRS assumption is estimated as

$$\theta^* = min\theta \qquad (19)$$

subject to

$$\sum_{j=1}^{n} \lambda_j x_{ij} \leq \theta x_{io} \qquad i = 1,2,\dots,m; \qquad (20)$$

$$\sum_{j=1}^{n} \lambda_j y_{rj} \geq y_{ro} \qquad r = 1,2,\dots,s; \qquad (21)$$

$$\lambda_j \geq 0 \qquad (22)$$

and TE under output-oriented based on CRS assumption is described as

$$\emptyset^* = max\emptyset \qquad (23)$$

subject to

$$\sum_{j=1}^{n} \lambda_j x_{ij} \leq x_{io} \qquad i = 1,2,\dots,m; \qquad (24)$$

$$\sum_{j=1}^{n} \lambda_j y_{rj} \geq \emptyset y_{ro} \qquad r = 1,2,\dots,s; \qquad (25)$$

$$\lambda_j \geq 0 \qquad (26)$$

Finally, $SE(\mathrm{X}_j, Y_j)$ and $TE(X_j, Y_j)$ for each DMU is given by

$$SE(X_j, Y_j) = \frac{\theta_j^* CCR}{\theta_j^* BCC} \qquad j = 1,\dots,n \qquad (27)$$

for input-oriented BCC model,

$$SE(X_j, Y_j) = \frac{\emptyset_j^{*}CCR}{\emptyset_j^{*}BCC} \qquad j = 1, \dots, n \qquad (28)$$

for output-oriented BCC model,

$$TE\ (X_j, Y_j) = 1 - SE(X_j, Y_j) \qquad j = 1, \dots, n. \qquad (29)$$

and for TE.

## 3.4 Analytical framework

This paper uses the output-oriented BCC model to estimate an efficiency of R&D productivity in 1340 national R&D projects of Korea renewable energy technology who received public R&D in order to test the hypothesis “R&D productivity of firms within Korea renewable energy industry is proportionally relevant to the size of the firms” where performers include large firms and smaller firms as well as universities and government-supported research institutes (institutes, in short).

An assumption of technological push that will enhance economic growth and social welfare is utilized for the analysis. In addition, in order to satisfy the homogeneity condition that the DMU should be operated under a similar purpose, the projects are distinguished by the technical progress phase (basic, applied, and development). Basic research is performed to obtain new knowledge, applied research to acquire knowledge for the practical application of science, and development research to have practical products with economical value to sell in the market.

Two input and five output variables whose data in every DMU are accessible through the National Technical Information Service (NTIS) system are chosen to analysis. The input and output data from the 1340 projects called DMUs are year-based data, and the DMUs that did not receive R&D support are not counted. In other words, data of the R&D project whose research period is at least more than two or three years are divided into each year. The input variables considered are pubic R&D financial support as well as firms’ private R&D investment and number of workers, regardless of their academic background. As output variables, five direct outputs without economic value—number of Scientific citation index (SCI) and non-SCI paper publications, number of applied

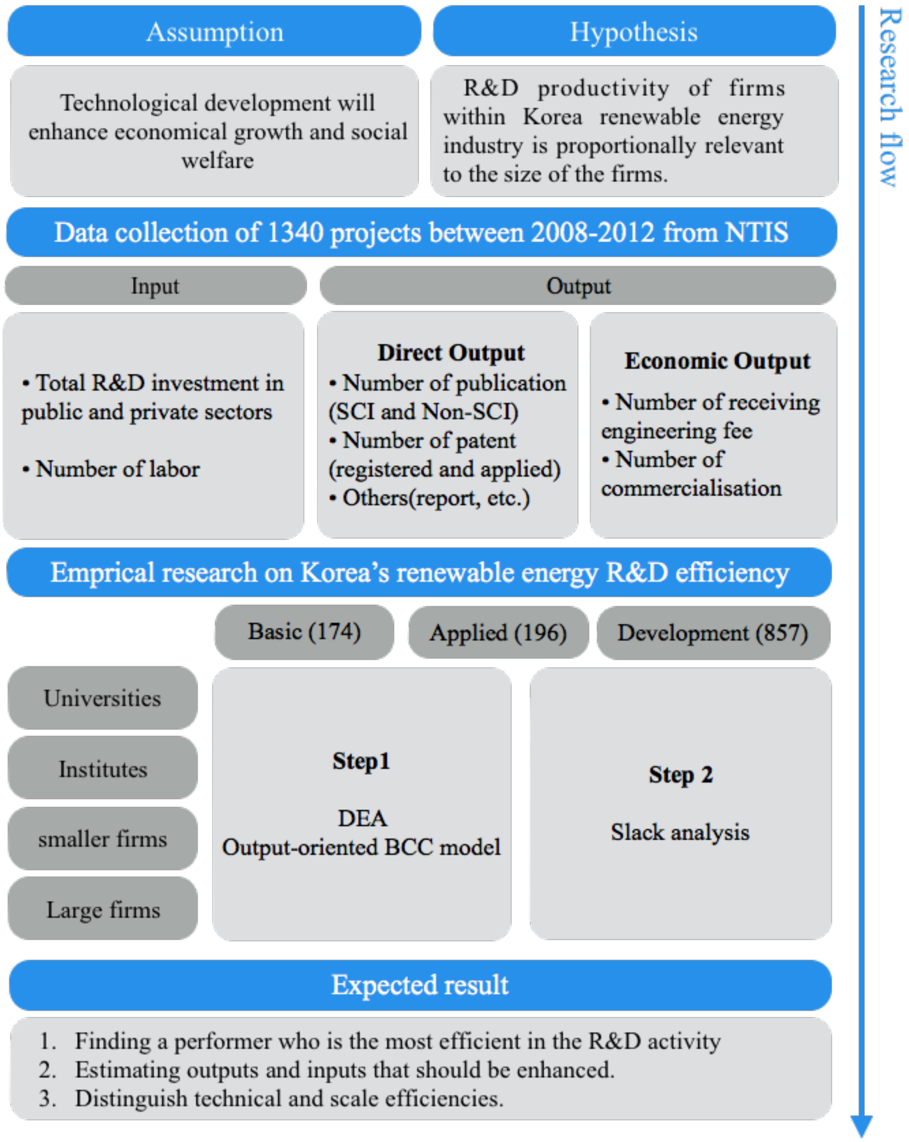



Figure 3.2. Analytical framework to analyse R&D efficiency in Korea renewable energy

and registered patents, and others without economical value such as report, prototype, etc.—and two economic outputs—number of receiving engineering fee and number of commercialization—are considered. The time lag from inputs to outputs is naturally not needed to consider for this analysis, since the output data is discovered in practice if occurred in the NTIS system and the efficiency of DMUs that have fewer or no outputs is to appear less efficient compared to other DMUs.

This study considers three direct outputs of number of publications, number of patents registered and applied, and any other forms and two economic outputs of number of receiving engineering fee and number of commercialisation. Paper publication is an objective indicator for basic research, and SCI papers are regarded as having higher quality than non-SCI papers. However, due to the lower number of publications that would not be representative as output variable and the language barrier that SCI paper are generally written in English, non-SCI papers are also counted as one of the output variables. Likewise, the registered patent, which is obtainable when the invention is considered to have new technological characteristics, is superior in quality but smaller in number than the applied patent; nevertheless, the applied patent is brought to supplement the quantitative profile. As an economic output, engineering fee in the private sector is generated when one party uses the right in asset or intellectual property owned by others. On the other hand, the engineering fee that is supported by public R&D is obtained when the relevant R&D is successfully commercialized, and some part of benefit is returned to the government. In addition, when the product is sold in the market, the product can be considered commercialized.

Thus, the projects are classified into basic, applied, and development as a first step and estimated by output-oriented BCC model of DEA and slack analysis by performer as follows. The data are collected from the NTIS and the period covered by this study is from 2008 to 2012, when R&D investment was geometrically increased and the project that is expected to commercialize was realized in the Korean renewable energy technology. The NTIS data shows the direct inputs on each R&D project as an amount of investment and human resources in number as well as direct performances as SCI paper, non-SCI paper, registered patent, applied papers, engineering fee and commercialization by year. That is, the time lag from R&D investment to commercialization stage is automatically considered.

## 3.5 Empirical research

The descriptive statistic of data from 2008 to 2012 is shown in Table 1 as below. During the period, 1340 projects were performed for renewable energy technologies under the supervision of Korea Energy Technology Evaluation and Planning (KETEP): 280 for large firms, 380 for smaller firms, 343 for institutes, 316 for universities, and 21 for others.

Data are classified according to technical progress phase and performers. In basic research, a large amount of R&D investment and workers are dedicated to universities and institutes, accounted for 71.3% of total R&D investment and 76.5% in total number of workers. On the other hand, average R&D investment and number of R&D workers are the higher in the large firms, which performed only 10 basic research programs, compared to the universities and institutes, which conducted 82 and 60, respectively, during the same period. R&D investment and workers in smaller firms are the least among the performers, but the average is higher than those for universities are and institutes though lower than that for large firms. In terms of the outputs, the direct outputs are more produced in universities and institutes both in total and average, but less in economical outputs presented as engineering fee and commercialization. The outputs as applied research accomplished in number gives weight to institutes.

In applied research, a share of R&D investment and workers in the institutes are the most between performers but the large firms are still the largest beneficiary per project. Similarly, for basic research, the institutes beside the inputs and the economical outputs are lower than the firms'. It is notable that the smaller firms produce more economic outputs than large firms compared with the inputs, the least in total amount among performers.

The researches on development phase has the largest share of R&D investment and workers in total compared to other research phases since they are believed to generate economical returns on the R&D spend. The large firms account for the largest proportion of R&D investment and workers, with 67.6% and 65.7%, respectively, and are assumed to perform larger projects relative to those of other performers. Smaller firms have the next highest proportions for both figures. The absolute total figures in outputs are superior to those of other research in different technical phases, but it is noticeable that the averages are not distinctly different among performers.

### 3.5.1 Data

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Data are classified according to technical progress phase and performers. In basic research, a large amount of R&D investment and workers are dedicated to universities and institutes, accounted for 71.3% of total R&D investment and 76.5% of the total number of research workers. On the other hand, average R&D investment and number of R&D workers are the larger in the large firms, which performed only 10 basic research programs, compared to the universities and institutes, which conducted 82 and 60, respectively, during the same period.

R&D investment and workers in smaller firms are the least among the performers, but the average is higher than those for universities are and institutes though lower than that for large firms. In terms of the outputs, the direct outputs are more produced in universities and institutes both in total and average, but less in economical outputs presented as engineering fee and commercialization. The outputs as applied research accomplished in number gives weight to institutes.

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### 3.5.2 Result

The result gained using the output-oriented VRS model is described in Table 3.2. as below. First of all, the efficiency of the 1,227 DMUs out of the 1340 DMUs including the researches that did not belong to any other technical progress phase is estimated by basic, applied, and development and then classified by performer as large and smaller firms, institutes, and universities. Thus, the results of efficiency and slack analysis shown in Table 2 are the average figures for each group by technical progress phase and by performer.

The overall average efficiency was 0.72 for basic, 0.60 for applied, and 0.50 for development research, which indicates the lowest efficiency score. Distinguishing the efficiencies by performer, universities' efficiency in basic research shows the highest 0.78 more than average, and the efficiencies in other performers are somewhat similar, though the large firms' are slightly lower. In DMUs in applied research, the efficiency in smaller firms is exceptionally higher than other performers', with 0.75, followed by large firms with 0.69; thus, the average efficiency scores of applied research in the firms exceed total average efficiency score of 0.60. The level of efficiencies in development research is almost alike among performers and it is also conspicuous that they are somewhat lower than those of other technical progress phases are.

According to the result showing the amount of input and output slacks that would be increased or decreased for improving efficiency, the estimated numerical values vary considerably among performers and technical progress phases. Regardless of performer, the results of efficient target that maximizes efficiency by manipulating inputs in R&D investment and labour to have maximum output level show that the current level of inputs are not required to achieve the current level of outputs. That is, outputs could be increased without increasing the current amount of inputs.

Moreover, DEA can provide information to show the DMUs whose efficiency score is one. The DMUs in basic research phases are the most efficient, while almost two thirds of DMUs in development phase, whose project accounts for nearly 70% of R&D in number, are inefficient. In other words, the projects in the development phases show the lowest efficiency in terms of number with the score of '1' compared to basic and applied researches. Looking at the results more in detail by performer, the combined smaller and large firms seem to perform more efficient R&D projects on average, with relatively more efficient value in applied research than universities and institutes. The

Table 3.1. Descriptive statistics of renewable energy R&D in Korea in 2008-2012

| | | Basic | | | | | | | Applied | | | | | | | Development | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Sum | Average | S.D. | Max | Min | | | Sum | Average | S.D. | Max | Min | | | Sum | Average | S.D. | Max | Min |
| Universities | R&D investment | 27,132.61 | 330.89 | 257.91 | 1,124.56 | 30.00 | Universities | R&D investment | 13,913.45 | 323.57 | 200.34 | 945.00 | 5.00 | Universities | R&D investment | 49,677.12 | 420.99 | 619.43 | 6,467.12 | 1.00 |
| | labor | 1,586.00 | 19.34 | 18.78 | 95.00 | - | | labor | 874.00 | 20.33 | 13.86 | 53.00 | 1.00 | | labor | 2,412.00 | 20.44 | 13.44 | 66.00 | 1.00 |
| | SCI paper | 139.00 | 4.48 | 4.52 | 20.00 | 1.00 | | SCI paper | 114.00 | 4.96 | 7.67 | 37.00 | 1.00 | | SCI paper | 298.00 | 4.97 | 8.89 | 50.00 | - |
| | Non-SCI paper | 62.00 | 2.48 | 2.21 | 10.00 | 1.00 | | Non-SCI paper | 67.00 | 4.79 | 6.21 | 24.00 | - | | Non-SCI paper | 215.00 | 4.48 | 6.01 | 36.00 | - |
| | registered patent | 30.00 | 2.14 | 1.92 | 7.00 | - | | registered patent | 14.00 | 2.00 | 2.45 | 8.00 | 1.00 | | registered patent | 40.00 | 1.67 | 1.62 | 7.00 | - |
| | applied patent | 64.00 | 2.67 | 2.58 | 12.00 | - | | applied patent | 26.00 | 2.00 | 1.41 | 6.00 | 1.00 | | applied patent | 153.00 | 2.51 | 2.27 | 12.00 | - |
| | others | 55.00 | 1.53 | 1.14 | 6.00 | - | | others | 35.00 | 1.67 | 1.28 | 6.00 | 1.00 | | others | 125.00 | 1.81 | 1.40 | 7.00 | - |
| | engineering fee | - | - | - | - | - | | engineering fee | - | - | - | - | - | | engineering fee | 4.00 | 0.80 | 0.75 | 2.00 | - |
| | commercialization | 1.00 | 0.50 | 0.50 | 1.00 | - | | commercialization | - | - | - | - | - | | commercialization | 5.00 | 1.00 | 1.26 | 3.00 | - |
| Institutes | R&D investment | 34,406.00 | 573.43 | 391.14 | 2,700.00 | - | Institutes | R&D investment | 78,020.38 | 896.79 | 934.50 | 6,205.00 | 70.00 | Institutes | R&D investment | 106,636.40 | 903.70 | 1,353.85 | 10,000.00 | 60.00 |
| | labor | 1,187.00 | 19.78 | 14.27 | 63.00 | - | | labor | 2,432.00 | 27.95 | 23.64 | 132.00 | 3.00 | | labor | 2,822.00 | 23.92 | 22.17 | 126.00 | - |
| | SCI paper | 59.00 | 3.11 | 2.12 | 9.00 | 1.00 | | SCI paper | 157.00 | 4.13 | 4.09 | 16.00 | - | | SCI paper | 120.00 | 2.86 | 2.82 | 17.00 | 1.00 |
| | Non-SCI paper | 47.00 | 2.35 | 1.65 | 6.00 | 1.00 | | Non-SCI paper | 73.00 | 2.35 | 1.98 | 9.00 | - | | Non-SCI paper | 141.00 | 3.20 | 4.65 | 29.00 | - |
| | registered patent | 14.00 | 1.56 | 0.68 | 3.00 | 1.00 | | registered patent | 17.00 | 1.00 | 0.77 | 3.00 | - | | registered patent | 50.00 | 2.00 | 1.77 | 6.00 | - |
| | applied patent | 70.00 | 2.80 | 2.45 | 11.00 | 1.00 | | applied patent | 140.00 | 3.33 | 3.01 | 13.00 | 1.00 | | applied patent | 226.00 | 3.90 | 3.90 | 16.00 | - |
| | others | 37.00 | 1.95 | 1.70 | 8.00 | 1.00 | | others | 95.00 | 1.79 | 1.52 | 10.00 | 1.00 | | others | 100.00 | 1.59 | 1.27 | 9.00 | - |
| | engineering fee | 1.00 | 1.00 | - | 1.00 | 1.00 | | engineering fee | 6.00 | 0.67 | 0.67 | 2.00 | - | | engineering fee | 10.00 | 0.67 | 0.47 | 1.00 | - |
| | commercialization | 3.00 | 1.00 | - | 1.00 | 1.00 | | commercialization | 1.00 | 0.20 | 0.40 | 1.00 | - | | commercialization | 14.00 | 1.17 | 1.86 | 7.00 | - |
| Smaller firms | R&D investment | 10,875.28 | 604.18 | 489.67 | 1,882.00 | 70.27 | Smaller firms | R&D investment | 16,298.51 | 493.89 | 313.49 | 2,000.00 | 50.00 | smaller firms | R&D investment | 314,032.92 | 1,019.59 | 1,208.88 | 9,408.00 | 1.00 |
| | labor | 414.00 | 23.00 | 16.09 | 59.00 | 4.00 | | labor | 573.00 | 17.36 | 10.56 | 57.00 | - | | labor | 7,764.00 | 25.21 | 22.76 | 121.00 | - |
| | SCI paper | 3.00 | 3.00 | - | 3.00 | 3.00 | | SCI paper | 1.00 | 1.00 | - | 1.00 | 1.00 | | SCI paper | 126.00 | 3.71 | 8.13 | 44.00 | - |
| | Non-SCI paper | 1.00 | 1.00 | - | 1.00 | 1.00 | | Non-SCI paper | 5.00 | 1.25 | 0.43 | 2.00 | 1.00 | | Non-SCI paper | 96.00 | 1.81 | 1.29 | 5.00 | - |
| | registered patent | 4.00 | 1.00 | - | 1.00 | 1.00 | | registered patent | 6.00 | 1.50 | 0.50 | 2.00 | 1.00 | | registered patent | 62.00 | 1.59 | 1.48 | 8.00 | - |
| | applied patent | 5.00 | 1.67 | 0.94 | 3.00 | 1.00 | | applied patent | 7.00 | 1.75 | 0.83 | 3.00 | 1.00 | | applied patent | 228.00 | 2.38 | 2.51 | 17.00 | - |
| | others | 7.00 | 1.17 | 0.37 | 2.00 | 1.00 | | others | 8.00 | 1.00 | - | 1.00 | 1.00 | | others | 226.00 | 1.54 | 1.54 | 15.00 | - |
| | engineering fee | 5.00 | 1.67 | 0.94 | 3.00 | 1.00 | | engineering fee | 8.00 | 1.14 | 0.35 | 2.00 | 1.00 | | engineering fee | 116.00 | 1.21 | 0.61 | 4.00 | - |
| | commercialization | - | - | - | - | - | | commercialization | 5.00 | 2.50 | 1.50 | 4.00 | 1.00 | | commercialization | 96.00 | 1.92 | 1.47 | 7.00 | - |
| Large firms | R&D investment | 13,879.72 | 1,387.97 | 1,409.39 | 4,363.05 | 362.00 | Large firms | R&D investment | 71,995.64 | 3,130.25 | 2,993.17 | 11,600.00 | 150.00 | Large firms | R&D investment | 556,431.74 | 2,588.05 | 3,181.99 | 24,456.85 | 32.00 |
| | labor | 438.00 | 43.80 | 24.05 | 106.00 | 23.00 | | labor | 2,037.00 | 88.57 | 67.41 | 317.00 | 10.00 | | labor | 15,001.00 | 69.77 | 151.11 | 2,072.00 | - |
| | SCI paper | 1.00 | 1.00 | - | 1.00 | 1.00 | | SCI paper | 9.00 | 1.80 | 0.98 | 3.00 | 1.00 | | SCI paper | 153.00 | 2.89 | 4.11 | 26.00 | - |
| | Non-SCI paper | 7.00 | 1.75 | 1.30 | 4.00 | 1.00 | | Non-SCI paper | 9.00 | 2.25 | 1.64 | 5.00 | 1.00 | | Non-SCI paper | 205.00 | 3.15 | 5.92 | 44.00 | - |
| | registered patent | 3.00 | 3.00 | - | 3.00 | 3.00 | | registered patent | 7.00 | 2.33 | 0.94 | 3.00 | 1.00 | | registered patent | 89.00 | 2.34 | 3.21 | 14.00 | - |
| | applied patent | 3.00 | 3.00 | - | 3.00 | 3.00 | | applied patent | 33.00 | 4.13 | 6.15 | 20.00 | 1.00 | | applied patent | 403.00 | 4.80 | 6.91 | 39.00 | - |
| | others | 3.00 | 1.00 | - | 1.00 | 1.00 | | others | 17.00 | 2.13 | 1.96 | 7.00 | 1.00 | | others | 284.00 | 2.51 | 2.59 | 15.00 | - |
| | engineering fee | 3.00 | 3.00 | - | 3.00 | 3.00 | | engineering fee | 4.00 | 1.00 | - | 1.00 | 1.00 | | engineering fee | 131.00 | 2.08 | 5.00 | 40.00 | - |
| | commercialization | 2.00 | 2.00 | - | 2.00 | 2.00 | | commercialization | 1.00 | 1.00 | - | 1.00 | 1.00 | | commercialization | 49.00 | 1.69 | 1.58 | 6.00 | - |

Table 3.2. efficiency of R&D productivity of Korea national R&D projects in renewable energy technology

| | | Total | | | Universities | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Technical progress phase | | Basic | Applied | Development | Basic | | Applied | | Development | |
| Efficiency | | 0.72 | 0.60 | 0.50 | 0.78 | | 0.58 | | 0.50 | |
| Input Slacks | Gov. R&D | 170.60 | 310.73 | 571.55 | 76.02 | | 72.20 | | 126.80 | |
| | Pri.R&D | 46.86 | 148.77 | 220.74 | 23.23 | | 33.36 | | 17.04 | |
| | Labor | 4.37 | 11.27 | 18.43 | 2.98 | | 5.91 | | 10.85 | |
| Output Slacks | SCI Paper | 0.77 | 3.95 | 0.32 | 0.70 | | 2.10 | | 0.03 | |
| | Non-SCI Paper | 0.74 | 2.00 | 0.72 | 0.62 | | 2.45 | | 0.98 | |
| | Reg. Patent | 0.51 | 1.03 | 0.47 | 0.44 | | 1.36 | | 0.47 | |
| | App. Patent | 0.48 | 0.51 | 0.84 | 0.43 | | 0.64 | | 0.75 | |
| | Others | 0.38 | 0.75 | 0.95 | 0.26 | | 0.76 | | 0.94 | |
| | Engineeringfee | 0.05 | 0.04 | 0.22 | 0.04 | | 0.02 | | 0.29 | |
| | Commercilisaiton | 0.08 | 0.00 | 0.02 | 0.07 | | 0.00 | | 0.00 | |
| Efficient Input Target | Gov. R&D | 269.49 | 500.53 | 522.09 | 215.14 | Variation | 213.96 | Variation | 249.11 | Variation |
| | Pri.R&D | 7.60 | 3.77 | 6.38 | 3.15 | | 0.14 | | 3.89 | |
| | R&D investment | 277.09 | 504.30 | 528.47 | 218.29 | -34.03% | 214.10 | -33.83% | 253.00 | -39.90% |
| | Labor | 16.54 | 30.41 | 17.84 | 15.88 | -17.91% | 60.46 | 197.47% | 10.44 | -48.92% |
| Efficient Output Target | SCI Paper | 2.77 | 8.21 | 3.33 | 3.24 | -27.63% | 9.23 | 86.22% | 6.33 | 27.44% |
| | Non-SCI Paper | 1.88 | 4.42 | 3.62 | 1.70 | -31.47% | 5.50 | 14.84% | 5.12 | 14.33% |
| | Reg. Patent | 0.96 | 1.42 | 1.05 | 0.91 | -57.67% | 1.78 | -10.90% | 1.24 | -25.51% |
| | App. Patent | 1.95 | 2.67 | 4.86 | 1.64 | -38.59% | 1.96 | -2.22% | 4.10 | 63.41% |
| | Others | 1.37 | 2.61 | 4.68 | 1.27 | -16.83% | 2.44 | 46.45% | 4.36 | 140.82% |
| | Engineeringfee | 0.10 | 0.14 | 1.27 | 0.04 | 0.00% | 0.02 | 0.00% | 0.36 | -54.47% |
| | Commercilisaiton | 0.11 | 0.06 | 0.42 | 0.08 | -83.48% | 0.00 | 0.00% | 0.05 | -95.08% |
| Frequency(%) | 0.00 | 0 (0%) | 0 (0%) | 0 (0%) | 0 (0%) | | 0 (0%) | | 0 (0%) | |
| | 0.01 -0.10 | 3 (1.8%) | 12 (6.5%) | 128 (15.4%) | 1 (1.2%) | | 2 (4.7%) | | 15 (11.2%) | |
| | 0.11 - 0.20 | 13 (7.6%) | 21 (11.3%) | 155 (18.7%) | 5 (6.1%) | | 5 (11.6%) | | 25 (18.7%) | |
| | 0.21 - 0.30 | 14 (8.2%) | 29 (15.6%) | 92 (11.1%) | 3 (3.7%) | | 10 (23.3%) | | 22 (16.4%) | |
| | 0.31 - 0.40 | 9 (5.3%) | 18 (9.7%) | 63 (7.6%) | 4 (4.9%) | | 3 (7%) | | 6 (5.7%) | |
| | 0.41 - 0.50 | 13 (7.6%) | 10 (5.4%) | 45 (5.4%) | 6 (7.3%) | | 2 (4.7%) | | 5 (3.7%) | |
| | 0.51 - 0.60 | 9 (5.3%) | 7 (3.8%) | 32 (3.9%) | 4 (4.9%) | | 1 (2.3%) | | 7 (5.2%) | |
| | 0.61 - 0.70 | 7 (4.1%) | 6 (3.2%) | 22 (2.7%) | 2 (2.4%) | | 2 (4.7%) | | 6 (4.5%) | |
| | 0.71 - 0.80 | 11 (6.4%) | 3 (1.6%) | 12 (1.4%) | 7 (8.5%) | | 1 (2.3%) | | 3 (2.2%) | |
| | 0.81 - 0.90 | 5 (2.9%) | 1 (0.5%) | 12 (1.4%) | 4 (4.9%) | | 0 (0%) | | 3 (2.2%) | |
| | 0.91 - 0.99 | 5 (2.9%) | 4 (2.2%) | 8 (1.0%) | 5 (6.1%) | | 1 (2.3%) | | 2 (1.5%) | |
| | 1.00 | 82 (48%) | 75 (40.3%) | 261 (31.4%) | 41 (50%) | | 16 (37.2%) | | 37 (27.6%) | |
| Efficiency | Technical Efficiency | 0.76 | 0.67 | 0.69 | 0.83 | | 0.67 | | 0.79 | |
| | Scale Efficiency | 0.24 | 0.33 | 0.31 | 0.17 | | 0.33 | | 0.21 | |
| Return to scale | Decreasing | 91 (53.8%) | 123 (66.1%) | 537 (66.2%) | 41 (50.0%) | | 29 (67.4%) | | 82 (61.2%) | |
| | Constant | 71 (42.0%) | 63 (33.9%) | 213 (26.3%) | 38 (46.3%) | | 14 (32.6%) | | 33 (24.6%) | |
| | Increasing | 7 (4.1%) | 0 (0.0%) | 61 (7.5%) | 3 (3.7%) | | 0 (0.0%) | | 19 (14.2%) | |

| | | Institutes | | | | | |
|---|---|---|---|---|---|---|---|
| Technical progress phase | | Basic | | Applied | | Development | |
| Efficiency | | 0.68 | | 0.53 | | 0.47 | |
| Input Slacks | Gov. R&D | 226.94 | | 230.07 | | 335.91 | |
| | Pri.R&D | 4.38 | | 17.09 | | 4.73 | |
| | Labor | 5.06 | | 6.11 | | 8.09 | |
| Output Slacks | SCI Paper | 0.43 | | 4.28 | | 0.51 | |
| | Non-SCI Paper | 0.94 | | 2.82 | | 1.17 | |
| | Reg. Patent | 0.51 | | 1.26 | | 0.64 | |
| | App. Patent | 0.37 | | 0.60 | | 0.93 | |
| | Others | 0.44 | | 0.67 | | 0.89 | |
| | Engineeringfee | 0.08 | | 0.02 | | 0.23 | |
| | Commercilisaiton | 0.11 | | 0.00 | | 0.00 | |
| Efficient Input Target | Gov. R&D | 334.92 | Variation | 648.65 | Variation | 628.81 | Variation |
| | Pri.R&D | 1.24 | | 0.97 | | 2.59 | |
| | R&D investment | 336.16 | -41.38% | 649.62 | -27.56% | 631.39 | -30.13% |
| | Labor | 14.76 | -25.39% | 21.84 | -21.87% | 14.78 | -38.19% |
| Efficient Output Target | SCI Paper | 2.34 | -24.58% | 9.80 | 137.09% | 4.68 | 63.91% |
| | Non-SCI Paper | 2.22 | -5.69% | 5.53 | 134.87% | 4.62 | 44.10% |
| | Reg. Patent | 0.85 | -45.22% | 1.66 | 65.71% | 1.32 | -33.77% |
| | App. Patent | 2.39 | -14.62% | 3.61 | 8.25% | 7.21 | 84.95% |
| | Others | 1.38 | -29.18% | 3.26 | 81.63% | 4.02 | 153.55% |
| | Engineeringfee | 0.10 | -90.31% | 0.09 | -85.90% | 0.65 | -3.15% |
| | Commercilisaiton | 0.16 | -83.88% | 0.01 | -92.56% | 0.24 | -79.26% |
| Frequency(%) | 0.00 | 0 (0%) | | 0 (0%) | | 0 (0%) | |
| | 0.01 -0.10 | 0 (0%) | | 6 (6.9%) | | 11 (8.1%) | |
| | 0.11 - 0.20 | 5 (8.2%) | | 11 (12.6%) | | 31 (23.0%) | |
| | 0.21 - 0.30 | 7 (11.5%) | | 14 (16.1%) | | 22 (16.3%) | |
| | 0.31 - 0.40 | 5 (8.2%) | | 14 (16.1%) | | 13 (9.6%) | |
| | 0.41 - 0.50 | 4 (6.6%) | | 7 (8.0%) | | 6 (4.4%) | |
| | 0.51 - 0.60 | 5 (8.2%) | | 2 (2.3%) | | 8 (5.9%) | |
| | 0.61 - 0.70 | 4 (6.6%) | | 4 (4.6%) | | 5 (3.7%) | |
| | 0.71 - 0.80 | 4 (6.6%) | | 0 (0%) | | 3 (2.2%) | |
| | 0.81 - 0.90 | 0 (0%) | | 1 (1.1%) | | 2 (1.5%) | |
| | 0.91 - 0.99 | 0 (0%) | | 3 (3.4%) | | 2 (1.5%) | |
| | 1.00 | 27 (44.3%) | | 25 (28.7%) | | 32 (23.7%) | |
| Efficiency | Technical Efficiency | 0.75 | | 0.53 | | 0.68 | |
| | Scale Efficiency | 0.25 | | 0.47 | | 0.32 | |
| Return to scale | Decreasing | 36 (61.0%) | | 69 (79.3%) | | 98 (68.5%) | |
| | Constant | 21 (35.6%) | | 18 (20.7%) | | 30 (21.0%) | |
| | Increasing | 2 (3.4%) | | 0 (0.0%) | | 15 (10.5%) | |

| | | Smaller firms | | | | | |
|---|---|---|---|---|---|---|---|
| Technical progress phase | | Basic | | Applied | | Development | |
| Efficiency | | 0.69 | | 0.75 | | 0.52 | |
| Input Slacks | Gov. R&D | 227.82 | | 239.80 | | 458.14 | |
| | Pri.R&D | 55.05 | | 71.58 | | 129.97 | |
| | Labor | 3.38 | | 10.19 | | 13.70 | |
| Output Slacks | SCI Paper | 1.18 | | 3.35 | | 0.35 | |
| | Non-SCI Paper | 0.95 | | 0.64 | | 0.44 | |
| | Reg. Patent | 0.34 | | 0.23 | | 0.51 | |
| | App. Patent | 0.26 | | 0.34 | | 0.76 | |
| | Others | 0.49 | | 0.62 | | 1.00 | |
| | Engineeringfee | 0.00 | | 0.05 | | 0.20 | |
| | Commercilisaiton | 0.00 | | 0.00 | | 0.03 | |
| Efficient Input Target | Gov. R&D | 255.56 | Variation | 163.26 | Variation | 414.31 | Variation |
| | Pri.R&D | 40.52 | | 19.25 | | 4.88 | |
| | R&D investment | 296.09 | -50.99% | 182.52 | -63.05% | 419.19 | -58.89% |
| | Labor | 18.68 | -18.77% | 7.17 | -58.71% | 11.77 | -53.30% |
| Efficient Output Target | SCI Paper | 2.09 | -30.44% | 3.79 | 279.23% | 1.59 | -57.21% |
| | Non-SCI Paper | 1.01 | 0.93% | 1.30 | 4.33% | 1.97 | 8.75% |
| | Reg. Patent | 0.93 | -7.12% | 0.58 | -61.62% | 0.90 | -43.35% |
| | App. Patent | 1.53 | -8.19% | 0.70 | -60.13% | 3.79 | 59.43% |
| | Others | 1.46 | 24.83% | 1.40 | 39.64% | 4.59 | 198.27% |
| | Engineeringfee | 0.29 | -82.78% | 0.36 | -68.63% | 1.67 | 38.21% |
| | Commercilisaiton | 0.00 | 0.00% | 0.16 | -93.59% | 0.63 | -67.22% |
| Frequency(%) | 0.00 | 0 (0%) | | 0 (0%) | | 0 (0%) | |
| | 0.01 -0.10 | 1 (5.6%) | | 2 (6.1%) | | 59 (18.2%) | |
| | 0.11 - 0.20 | 1 (5.6%) | | 2 (6.1%) | | 57 (17.6%) | |
| | 0.21 - 0.30 | 3 (16.7%) | | 3 (9.1%) | | 31 (9.6%) | |
| | 0.31 - 0.40 | 0 (0%) | | 0 (0%) | | 19 (5.9%) | |
| | 0.41 - 0.50 | 2 (5.6%) | | 1 (3.0%) | | 18 (5.6%) | |
| | 0.51 - 0.60 | 0 (0%) | | 3 (9.1%) | | 9 (2.8%) | |
| | 0.61 - 0.70 | 1 (5.6%) | | 0 (0%) | | 8 (2.5%) | |
| | 0.71 - 0.80 | 0 (0%) | | 2 (6.1%) | | 1 (0.3%) | |
| | 0.81 - 0.90 | 1 (5.6%) | | 0 (0%) | | 6 (1.9%) | |
| | 0.91 - 0.99 | 0 (0%) | | 0 (0%) | | 1 (0.3%) | |
| | 1.00 | 9 (50%) | | 20 (60.6%) | | 115 (35.5%) | |
| Efficiency | Technical Efficiency | 0.81 | | 0.84 | | 0.74 | |
| | Scale Efficiency | 0.19 | | 0.16 | | 0.26 | |
| Return to scale | Decreasing | 8 (44.4%) | | 14 (42.4%) | | 149 (71.0%) | |
| | Constant | 8 (44.4%) | | 19 (57.6%) | | 45 (21.4%) | |
| | Increasing | 2 (11.1%) | | 0 (0%) | | 16 (7.6%) | |

| | | Large firms | | | | | |
|---|---|---|---|---|---|---|---|
| Technical progress phase | | Basic | | Applied | | Development | |
| Efficiency | | 0.61 | | 0.69 | | 0.50 | |
| Input Slacks | Gov. R&D | 505.13 | | 1144.91 | | 1146.15 | |
| | Pri.R&D | 480.77 | | 968.16 | | 588.22 | |
| | Labor | 13.38 | | 43.64 | | 36.43 | |
| Output Slacks | SCI Paper | 2.59 | | 5.61 | | 0.32 | |
| | Non-SCI Paper | 0.19 | | 0.65 | | 0.71 | |
| | Reg. Patent | 1.40 | | 0.55 | | 0.34 | |
| | App. Patent | 2.01 | | 0.23 | | 0.92 | |
| | Others | 0.83 | | 1.08 | | 0.95 | |
| | Engineeringfee | 0.02 | | 0.05 | | 0.20 | |
| | Commercilisaiton | 0.04 | | 0.00 | | 0.01 | |
| Efficient Input Target | Gov. R&D | 347.67 | Variation | 1017.18 | Variation | 773.77 | Variation |
| | Pri.R&D | 23.00 | | 0.00 | | 12.52 | |
| | R&D investment | 336.16 | -75.78% | 649.62 | -79.25% | 631.39 | -75.60% |
| | Labor | 29.80 | -31.97% | 44.93 | -49.27% | 32.13 | -53.95% |
| Efficient Output Target | SCI Paper | 2.69 | 169.17% | 6.20 | 244.47% | 3.34 | 15.86% |
| | Non-SCI Paper | 2.94 | 67.87% | 2.14 | -4.95% | 4.09 | 29.55% |
| | Reg. Patent | 2.04 | -32.05% | 0.96 | -59.06% | 1.02 | -56.57% |
| | App. Patent | 2.65 | -11.58% | 3.63 | -12.01% | 5.53 | 15.25% |
| | Others | 1.98 | 97.93% | 2.54 | 19.59% | 5.31 | 111.13% |
| | Engineeringfee | 0.32 | -89.20% | 0.23 | -77.38% | 1.68 | -19.25% |
| | Commercilisaiton | 0.24 | -88.00% | 0.04 | -95.65% | 0.43 | -74.48% |
| Frequency(%) | 0.00 | 0 (0%) | | 0 (0%) | | 0 (0%) | |
| | 0.01 -0.10 | 1 (10.0%) | | 2 (8.7%) | | 43 (18.1%) | |
| | 0.11 - 0.20 | 2 (20.0%) | | 3 (13.0%) | | 42 (17.7%) | |
| | 0.21 - 0.30 | 1 (10.0%) | | 2 (8.7%) | | 17 (7.2%) | |
| | 0.31 - 0.40 | 0 (0%) | | 1 (4.3%) | | 22 (9.3%) | |
| | 0.41 - 0.50 | 1 (10.0%) | | 0 (0%) | | 16 (6.8%) | |
| | 0.51 - 0.60 | 0 (0%) | | 1 (4.3%) | | 8 (3.4%) | |
| | 0.61 - 0.70 | 0 (0%) | | 0 (0%) | | 3 (1.3%) | |
| | 0.71 - 0.80 | 0 (0%) | | 0 (0%) | | 5 (2.1%) | |
| | 0.81 - 0.90 | 0 (0%) | | 0 (0%) | | 1 (0.4%) | |
| | 0.91 - 0.99 | 0 (0%) | | 0 (0%) | | 3 (1.3%) | |
| | 1.00 | 5 (50.0%) | | 14 (60.9%) | | 77 (32.5%) | |
| Efficiency | Technical Efficiency | 0.67 | | 0.64 | | 0.56 | |
| | Scale Efficiency | 0.33 | | 0.36 | | 0.44 | |
| Return to scale | Decreasing | 6 (60%) | | 11 (47.8%) | | 208 (64.2%) | |
| | Constant | 4 (40%) | | 12 (52.2%) | | 105 (32.4%) | |
| | Increasing | 0 (0.0%) | | 0 (0.0%) | | 11 (3.4%) | |

number of DMUs with efficiency with score '1' in development research in the firms is slightly higher than in the universities and institutes. In addition, the efficiencies between small and large firms are also not notably different, and the efficiency in smaller firm is rather higher than large firms, at 35.5% and 32.5%, respectively.

It is necessary for this study to consider if there are efficiency of scale between DMUs since the efficiency can be increased or decreased as scale increases. The scale of R&D investment and labour as input variables, as well as their outputs produced in various forms, vary by performer and technical progress phase. As a result, regardless of characteristics divided by performer and technical progress phase, there is more in efficiency of scale than technical efficiency, meaning the efficiency is increased as the size of the DMU is increased.

## 3.6 Conclusion

In the previous sections, I used the output-oriented BCC model of the DEA to estimate the efficiency of R&D productivity among 1340 national R&D projects in renewable energy technology in Korea by performer and by technical progress phase. The DMUs are classified by level of technical progress phase (basic, applied, and development) as a first step to satisfy the homogeneity condition and the result of efficiencies are averaged by performer to verify the hypothesis.

The result explains one of the reasons why the industry development in renewable energy in Korea is not growing fast is. It also explains causes of the fact that firms' R&D productivity in the renewable energy technology is low. In fact, the large firms are proved to have several benefits in performing R&Ds compared to smaller firms, in spite of some weakness such as inflexible bureaucratic R&D management, and they are expected to have more fruitful results in outputs than another performer. Therefore, they invest a large amount of resources, including public financial support from government, as well as and human labour into the renewable technology, especially on development phase, for which they anticipate economic outcome in the short term.

However, while the efficiencies on basic and applied research are rather high in most performers, since direct outputs from R&D support are sufficiently created, most research on the development phase correlated to profitability performed mostly by firms are rather inefficient. This is because its economical outputs compared to initial R&D support are inadequately produced, though those performers are expecting R&D results with economic value. In addition, the efficiency in the smaller firms on the development phases show is slightly higher than large firms, who received the R&D support the most in amount as well as per project; thus, the hypothesis is rejected.

The result shows that efficiencies derive more from efficiency of scale than technical efficiency, meaning the R&D efficiency increases as quantities of R&D inputs increase, which should be considered in tackling how to improve R&D in a qualitative aspect. According to the research by Cohen and Klepper (1996) described earlier, the cost-spreading model is valid in the large business unit where the firm operates as one of diverse business rather than the whole size of the firm. Thus, it is needed to review whether the R&D investment and number of workers data should be made only according to the firm size rather than with consideration that the firm's business unit per se has an ability to make a result of the R&D culminate in real commercialization. Therefore, both ex-ante and ex-post analysis to understand firms' ability to complete R&D activity and to assess the R&D activity terminated are required to further enhance R&D productivity.

In addition, securing industrial competitiveness in the overseas renewable energy market is necessary through more efforts into R&D focused on the core technology. For the purpose of expanding the market share, smaller firms that possess unique R&D on the diversity of projects are able to play an important role, which also enables them to coexist with large firms. There is a mutual agreement of systemic cooperation between large firms that focus on systemic R&D process and smaller firms that improve components, equipment, or/and materials in Korean industry. Therefore, it is desirable to encourage more knowledge and technology sharing between smaller and large firms for mutual growth by localizing the renewable energy technology and further broadening markets overseas.

A further challenge of this paper is that it focuses on quantity-based output data for the analysis. For instance, some DMUs that produce a smaller number of papers or patent might produce papers or patents that are superior in quality. By the same logic, economical benefits counted in number of commercialization and engineering fee would increase for such DMUs

To expect domestic renewable industry as a new future growth engine, it requires strategies to expand the domestic demand limited for now to achieve a goal of GHGs reduction as well as strengthen an industrial base for overseas market expansion. Political supports to overseas' projects of renewable are also needed for Korean firms.

# 4 The Price of Photovoltaic Technology and the Impact of R&D

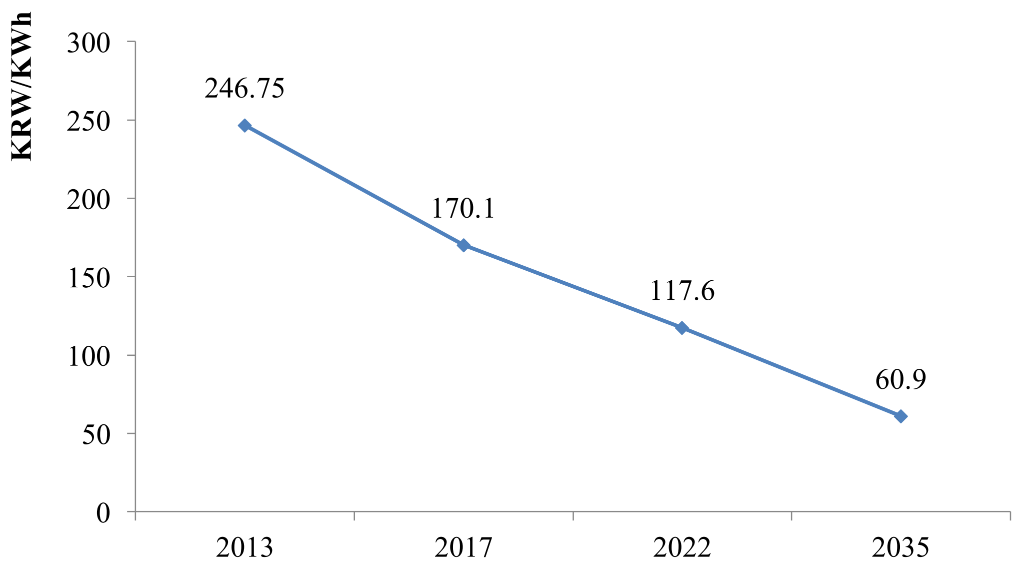
## 4.1 Introduction

Korea is an energy intensive country that needs to take radical action to diversify its energy sources and adhere to the international trend toward renewable energy use. In 2014, the nation's total primary energy supply (TPES) was 282.9 million tonne of oil equivalent (toe). The Second National Energy Basic Plan (2014-2035) includes a target for the supply of new and renewable energy to be 11% of the TPES by 2035. The renewable energy production in 2014 was 10,956 thousand toe, which is 3.87% of the TPES, while waste energy was 6,904 thousand toe and bio energy was 2,821 thousand toe.

The nation's total electricity generation in 2014 was 521.9 TWh, and the electricity sourced from renewable energy (excluding hydro power) was 14.7 TWh, which is 2.8% of the TPES. Excluding hydro power, which is often regarded as a non-renewable energy source because of its high technological maturity, solar photovoltaic (PV) energy plays a major role in providing clean electricity, producing 2,556 GWh, which is the largest share of electricity production by a renewable energy source. Wind power and fuel cells produced 1,145 GWh and 943 GWh of electricity, respectively, in 2014.

The share of new and renewable energy is planned to be 11.0% of the TPES by 2035 with an annual 6.2% average growth rate in accordance with the Second National Energy Basic Plan (2014-2035) and the Fourth Basic Plan for New and Renewable Energy. The main directions for the renewable energy diffusion plan are to decrease the share of waste energy that accounts for two-thirds of the current renewable energy and to foster PV and wind energy as core sources of energy. PV energy is planned to be 12.9% in 2025 and 14.1% in 2035 of the renewable energy of the TPES with an 11.7% annual average growth rate. Thus, 13.4% of the renewable energy of the total electricity generation will be supplied by PV to reach this target.

According to the "4th Basic Plan for New and Renewable Energy", the price of PV that will function as a significant renewable energy source in Korea is intended to decrease to KRW 60.9/kWh by 2035, as depicted in the Figure 4.1. The plan states that research and development (R&D) is continually required to decrease the price of PV, improve its competitiveness with other electricity sourced by traditional fossil fuels and nuclear




4th Basic Plan for New and Renewable Energy

Figure 4.1. Korean targeted PV generation price by 2035

power, and diffuse PV energy widely for national energy security and environmental impact.

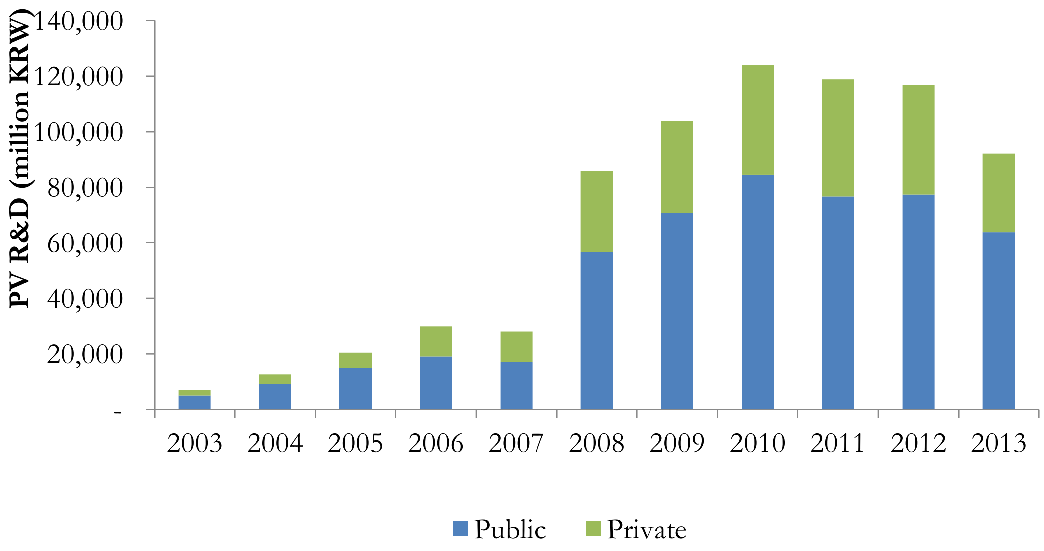
The large political instruments regarding renewable energy in Korea are the Renewable Portfolio Standard (RPS) and R&D subsidies. The RPS, which replaced Feed-in Tariff (FIT), was introduced in 2012 to enlarge the domestic market of renewable energy. The instrument mandates that electricity utilities that generate more than 500 MW must increase renewable energy production from 2% in 2012 to 10% in 2024. As of 2014, a cumulative capacity of 3.2 GW was newly installed, 1.2 GW of which are from PV energy (MOTIE, 2014).

Approximately 3.71 trillion KRW of Korea's R&D budget, comprised of 1.94 trillion KRW from the government (52.3%) and 1.77 trillion KRW (47.7%) from the private sector, has been dedicated to encouraging and improving renewable energy technology (MOTIE, 2014). The R&D budget for renewable energy sharply increased in 2008, and 74.5% of the total renewable energy R&D budget from 1988 to 2013 was allocated to four priority renewable energy sources: PV (26.6%), wind (15.9%), hydrogen and fuel cell (24.8%), and integrated gasification combined cycle (IGCC) (7.2%).

PV energy has been continuously and intensively promoted by R&D policy, as shown in Figure 4.2., with 641.5 billion KRW in investment, comprised of 429.4 billion KRW from the government with 9% annual average growth and the remaining from the private sector (MOTIE, 2014), to improve conversion efficiency to decrease the cost of the system and electricity generation and to make PV energy competitive against traditional energy resources, specifically fossil fuel and nuclear power.

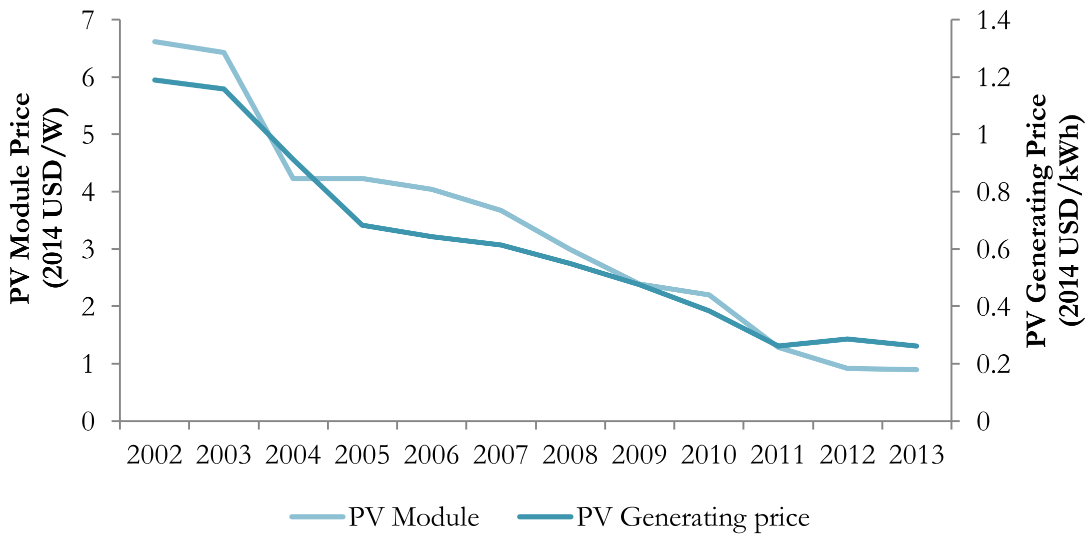
In addition, the policy also seeks to catch up with the existing advanced PV technology and future PV technologies, such as copper indium gallium selenide (CIGS) thin film solar cells, dye sensitized solar cells, and organic solar cells, to have a competitive advantage in the overseas market.

However, PV is struggling to diffuse and reduce costs despite a series of various efforts in the RPS and R&D support. For example, only 64.7% and 67.2% of the renewable energy certificates (RECs) were implemented in 2012 and 2013, respectively, indicating how the RPS as a diffusion policy failed to fulfil the entire original target. R&D investment is also problematic if the PV generation price will decrease enough to be




Source: MOTIE (2014)

Figure 4.2. Annual Korean PV R&D investment




Source: IEA (2013)

Figure 4.3. Korean PV module and energy generation prices

competitive with one of the traditional sources of energy, such as fossil fuel or nuclear power. In Korea, the average PV R&D share as a percentage of total investment has been around 6.1% over the past seven years. Thus, political advice has been suggested for Korea to obtain a more advanced and competitive level of PV technology to broaden its share in the national and overseas markets. The efficiency of PV R&D investment should improve in accordance with an in-depth evaluation to determine the obstacles for PV growth and suggest reform measures (KEEI, 2013; KISTEP 2014). It is important to evaluate the introduction of future renewable energy technology with R&D efforts because the performance of the technology could otherwise be underestimated, especially regarding the energy system model (Watanabe et al., 2003). Therefore, it is essential for Korea to have substantial reductions in PV price that correspond to the political efforts.

Considering that PV technology is expected to retain a major role in the Korean electricity market, this study aims to predict the future Korean PV generation prices under the current level of diffusion and R&D policies to discern if the technology can compete with the generation prices of traditional sources of power in the national electricity market. Therefore, the future price of a domestic PV module, which occupies the largest part of the generation price, is easily estimated. Figure 4.3. describes the PV module and generation prices from 2002 to 2013 in Korea. A PV module in 2002 cost USD 6.61/W, and declined to 0.89/W in 2013 (IEA, 2013). The PV generation price is estimated to have been USD 1.189/kWh in 2002, and decreased to USD 0.262/kWh in 2013. As mentioned earlier, the price is expected to decrease to KRW 60.9/kWh (approximately USD 0.06/kWh if KRW 1000 is converted as USD 0.91) by 2035.

## 4.2 Literature review

### 4.2.1 Previous studies

The exogenous growth model from the perspective of macroeconomics was advanced by Ramsey (1928) and Solow (1956), and considers long-term and stable economic growth as being determined exogenously, for example, technical shock or technical change as a result of innovation without compensation. However, in the recent endogenous growth model proposed by Romer (1986) and Lucas (1988), economic growth is based on accumulated knowledge and human capital, such that producing new knowledge that will be constantly developed is significant for economic growth. Therefore, R&D investment that brings about technical progress and technical innovation will shift the current technology and industry structure and ultimately influence economic growth.

Innovation is defined as “an idea, practice, or object that is perceived as new to an individual or another unit of adoption” by Everett Rogers (1995), who explains that innovation is developed through the processes of decision, activities, and impacts generated from the recognition of a problem or need to the basic and applied research, development, commercialization, adoption and diffusion, and consequences.

Here, the processes of basic and applied research and development are customarily referred to as R&D. That is, an invention is discovered or created from a new idea through basic and applied research and turns into an innovation after going through a development process where technological transfer occurs as the result of the research (Rogers, 2003). The learning effect that reduces the unit cost of a product is a function of the experience gained from the product’s cumulative output, research, use, and/or interaction in later stages of commercialization, adoption, and diffusion.

Wright (1936) first depicted the learning effect and showed that the total number of working hours decreases as the production level increases in airplane manufacturing. Arrow (1962) and Alchian (1963) developed the theory and several different mechanisms of learning were distinguished, such as learning-by-doing (LBD), learning-by-searching (LBS), learning-by-using (LBU), and learning-by-interacting (LBI) (Junginger et al., 2005, 2006; Grubler and Messner, 1998). An approach called the one factor learning curve (1FLC) is often applied to quantify the learning effect from LBD, and the approach has been extended to include LBS, which is called the two factor learning curve (2FLC) (Argot et al., 1990). Recently, active R&D has become a significant factor to lead technical change endogenously and should be considered when learning effects are estimated.

While the significance of energy diversification, along with fossil fuel depletion and environmental conservation from global warming and climate change is being stressed, renewable energy has garnered attention as being able to cope with these difficulties. International investment in technology development for renewable energy has increased dramatically during the last two decades, and some renewable energies, such as hydraulic, bio, waste, PV, and wind, have been commercialized and are performing a major role in supplying energy to some countries.

For example, two-thirds of Sweden's electricity is provided by renewable sources, and the country announced an ambitious plan to be the first fossil fuel-free country in a speech to the UN General Assembly (Bolton, 2015). However, uncompetitive generation costs for some renewables, such as PV and wind energy, is problematic to disseminating the energy, and several academic attempts have been made to analyse the prospects for reducing the cost of renewables by estimating the learning curves by the 1FLC (Neij, 1999; Junginger et al., 2005; Berglund et al, 2006; Nemet 2006; Albrecht, 2007; Pan et al., 2007; Soderholm et al., 2007; Kahouli-Brahmi, 2008; Ferioli, 2009).

R&D should not be disregarded since knowledge stock (KS) is significant for endogenous technical change and stable economic growth. The 2FLC incorporates the KS that is normally measured by past R&D investment in addition to the cumulative installed capacity or production of a certain technology, as is used in the 1FLC, and is more accurate to examine future energy price.

Therefore, this study will consider R&D impact on innovation and price reduction in technology and use 2FLC to expect future PV module price. In sequence, future PV generation price is estimated with an empirical tool of levelized cost of electricity (LCOE). The objective of the study is to determine if the price of a PV electricity system will reach the targeted PV generation prices by the given planned period presented in the Fourth Basic Plan for New and Renewable Energy. The sensitivity analysis is carried out to see how large R&D investment is expected to effect on price in future PV module and LCOE.

### 4.2.2 Empirical models

#### *Two Factor Learning Curve (2FLC)*

The 2FLC was introduced by Kouvaritakis et al. (2000). The model explains the relationships between cost reduction and cumulative capacity (CC), as well as the knowledge stock (KS) led by R&D activity. Therefore, from the two factors CC and KS, two learning curves are specified: one is the conventional "learning-by-doing" that explains the cost reduction as related to the CC, and the other is "learning-by-searching" that explains the KS as created by R&D activity to decrease the cost. The 2FLC can be demonstrated by Equation (1), presented as follows:

$$SC_{te,t}(CC,KS) = aCC_{te,t}^{-\alpha}KS_{te,t}^{-\beta} \qquad (1)$$

where

SC: Specific cost in one of currencies;

CC: Cumulative capacity;

KS: Knowledge stock;

te: Technology;

t: Time;

a: Specific cost at unit cumulative capacity and unit knowledge stock;

-$\alpha$: Learning-by-doing index; and

-$\beta$: Learning-by-searching index.

Therefore, the learning-by-doing rate (LDR) and the learning-by-searching rate (LSR) are derived from Equations (2) and (3) as follows:

$$LDR = 1 - 2^{-\alpha}; \qquad (2)$$

$$LSR = 1 - 2^{-\beta}. \qquad (3)$$

The specific technology cost decreases with the LDR for each doubling of CC and/or the LSR for each doubling of KS. The KS is estimated from the past R&D investment utilized for a given year for the technology, and a depreciation rate and time lag are taken into account. The KS is specified as Equation (4), as follows:

$$KS_{te,t} = KS_{te,t-1}(1-\rho) + ARD_{te,t-i} \qquad (4)$$

where

KS: Knowledge stock;

$\rho$: Knowledge stock depreciation;

ARD: Annual R&D expenditure;

te: Technology;

t: Time; and

i: Time lag between R&D expenditure and its effect.

The learning parameter is estimated by using Ordinary Least Squares (OLS), and is specified with an error term ($\varepsilon$), as Equation (5) follows:

$$\log(SC) = \log(a) + \alpha log(CC) + \beta log(KS) + \varepsilon. \qquad (5)$$

The models of selected studies using 2FLC for predicting PV cost is shown in Table 4.1. The studies using 2FLC are mostly panel studies to compare the future energy price among countries. The results described as LDR and LSR were discovered differently depending on the variables considered as measures of each study. The LDR and LSR in the international studies are, on average, 14% and 9%, respectively. A study in the United States estimated its LDR and LSR as approximately 13% and 10%, and a Japanese study found 15.7% and 13.2%, which represents higher rates than in the United States.

There has been limited research estimating PV prices in Korea. Park et al. (2012) used data from 1995 to 2010 and draw a time of grid parity in PV under various scenarios until 2030. According to a learning curve determined in a case of a 2 year time lag and a 10% depreciation rate for R&D, the PV generation price is expected to decrease to

Table 4.1. Selected PV studies using the 2FLC methodology

| Title | Author | Variables | | | | | | | PV Learning | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Place | Period | Knowledge Stock | | | Cumulative Capacity | Investment cost | LDR | LSR |
| | | | | R&D | Depreciation rate (%) | Time-lag (year) | | | | |
| Experiments with a methodology to model the role of R&D expenditures in energy technology learning processes; first results | Miketa et al.(2004) | intl. | 1971-1997 | Public & Private | 3 | 2 | Cumulative installed capacity (GW) | Investment cost/watt (USD'90) | 17.46% | 10.00% |
| Testing for the presence of some features of increasing returns to adoption factors in energy system dynamics: An analysis via the learning curve approach | Sodes Kaouli-Brahmi (2009) | intl. | 1977-1997 | Public & Private | 3 | 3 | Power generation capacity (MW) | Energy technology cost (USD/kW) | 7.34% | 0.69% |
| Long-term renewable energy technology valuation using system dynamics and Monte Carlo simulation: Photovolatic technology case | Jeon et al. (2014) | intl. | 1974-2011 | Public | 10 | 3 | Cumulative PV production (MW) | PV module Price (USD/Watt) | 12.18% | 12.16% |
| Technological learning and renewable energy costs: Implications for US renewable energy policy | Kobos et al. (2006) | intl. | 1975-2000 | Public | 10 | 3 | Cumulative shipments of PV modules (MW) | Manufacturer's price | 18.40% | 14.30% |
| The role of policy in PV industry growth: Past, present and future | Byrne et al.(2011) | USA | 1990-2008 | Public | 3 | 3-Feb | Cumulative installed capacity (MW) | System Cost (USD/W) | 13.10% | 10.00% |
| Quantification of technological learning by R&D and its application for renewable energy technologies | Hayamizu (2014) | Japan | 1990-2010 | Public & Private | 10% for public, 20% for private | 5 years for public, 3 years for private | Cumulative PV production (kW) | PV Installed price (USD/kW) | 15.70% | 13.20% |
| Forecasting the grid parity of solar photovoltaic energy using two factor learning curve model | Park et al. (2012) | Korea | 1995-2009 | Public & Private | 20-Oct | 4-Feb | Cumulative PV generation (MWh) | Installed Price (KRW/kW) | 1.9~4% | 15.5~23.5% |
| Scenario analysis for estimating the learning rate of photovoltaic power generation based on learning curve theory in South Korea | Hong et al. (2015) | Korea | 2004-2011 | Public | 20 | 3 | Cumulative PV generation (MWh) | Total PV transaction cost/total power trade (KRW/kWh) | 2% | 5% |

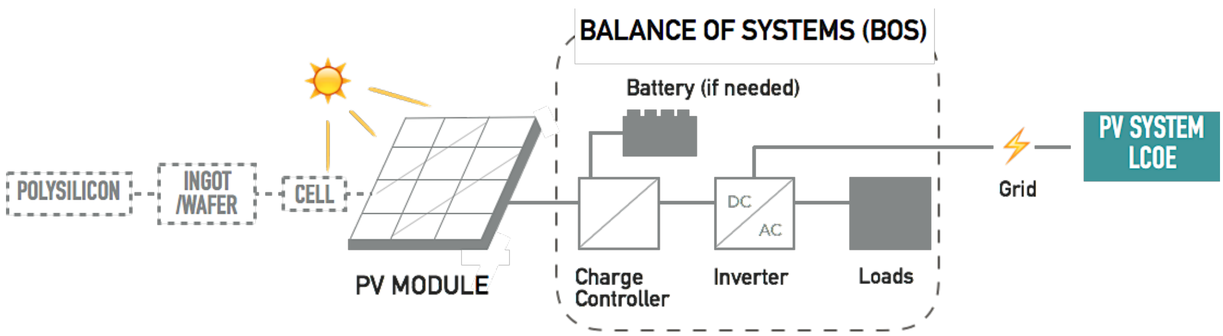



Figure 4.4. A value chain of wafer-based crystalline silicon (c-Si) PV

157 KRW/kWh in 2018, which is lower than the generation price of oil and liquefied natural gas (LNG). Hong et al. (2015) estimated PV generation cost with data from 2004 to 2011, and the cost decreased by 2.33% when the cumulative power generation doubled and by 5.13% every time R&D investment was doubled with 3 years of time lag and a 20% depreciation rate for R&D.

### *Levelised Cost of Electricity (LCOE)*

PV cells are divided largely into non-organic or organic according to the cell material. Non-organic PV cells are divided further depending on whether they are produced by silicon. The wafer-based crystalline silicon (c-Si) PV, which accounted for approximately 90% of the PV market in 2013, is separated into monocrystalline silicon (sc-Si) PV, that has commercial efficiency between 16% and 24%, and multicrystalline silicon (mc-Si) PV, that has an average conversion efficiency around 14 to 18% (IEA, 2014).

The wafer-based c-Si PV, which dominates the current market with mature technology obtained by knowledge accumulated within the electronic industry, is manufactured according to the value chain depicted in Figure 4.4. Polysilicon is the raw material for c-Si that is produced and transformed into the ingot, wafer, and cell, and is the smallest unit to convert solar energy into direct current electricity. The cell is then assembled as a PV module to obtain a large volume of electricity, and the produced electricity is transferred to the grid being supported by a balance of system (BOS).

The Levelised Cost of Electricity Generation (LCOE) is based on a discounted cash flow (DCF) where the present value of the total investment cost is divided by the average real generation cost per generating unit. The LCOE varies by technology and its technological level is measured as efficiency and performance, place and project, and investment in the technology. The formula to measure the PV LCOE is described as Equation (6), as follows:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \qquad (6)$$

where;

LCOE = Average lifetime levelised cost of electricity generation;

$I_t$= PV system price in the year t;

$M_t$= Operations and maintenance expenditures in the year t;

$F_t$ = Fuel expenditures in the year t;

$E_t$ = Electricity generation in the year t;

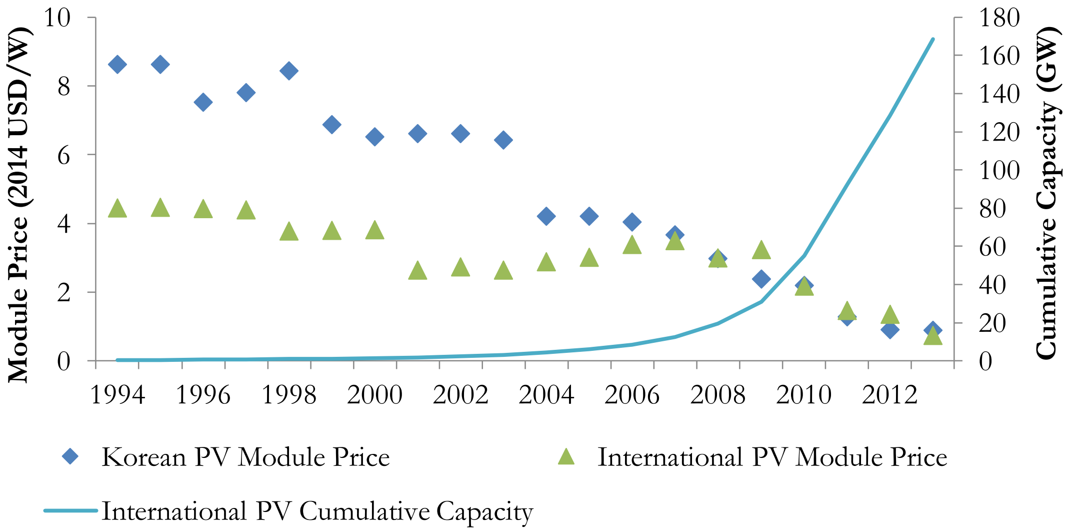
r = Discount rate; and

n = Economic life of the system.

The BOS, comprised of an inverter, charge controller, battery if needed, and other parts required supporting the system, occupies the largest portion of the PV system cost together with the PV module. The cost of the BOS largely varies depending on the nature of the installation, from 20% for a large-scale grid connected system to 70% for a smaller off-grid system. On average, the BOS is 40% of the cost for a standard utility-scale ground-mounted system (IRENA, 2012). Therefore, the PV module and BOS prices must be considered for PV LCOE analysis. Fuel expenditures (F), operations, and maintenance expenditures (M) are relatively lower than conventional fossil fuel and nuclear power plants (IRENA, 2012).

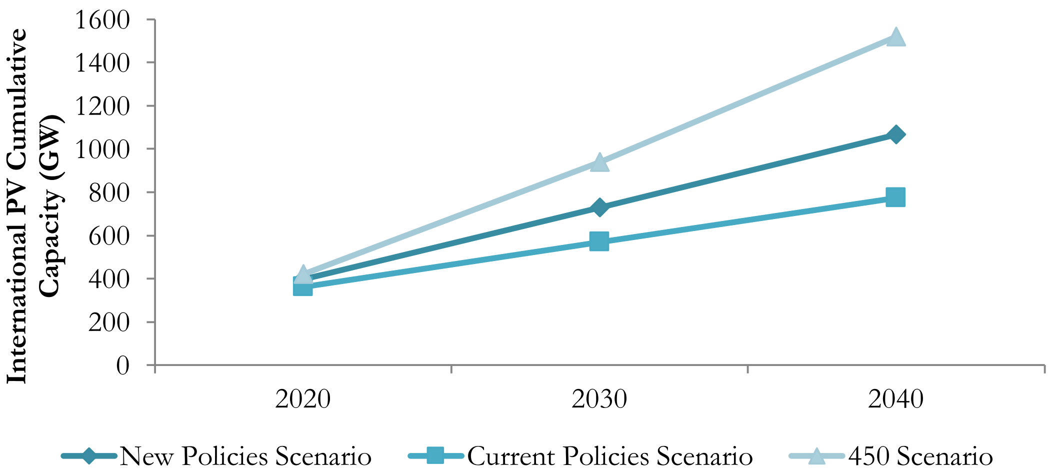
## 4.3 Analytical framework

The predicted future price of a domestic PV module is measured by a 2FLC. The period for obtaining LDR and LSR was between 1994 and 2013, where the nominal pricing values used for analysis have been converted into real values using the 2014 US GDP as a divisor. The specific investment cost (SC) is presented as the price of Korean PV module in 2014 USD currency per Watt (W), and the data was obtained from the "International Energy Agency Photovoltaic Power Systems (IEA-PVPS) National Survey Reports" reported from 2002 and 2013. As shown in Figure 4.5., the early Korean PV module price in 1994 was more than twice the international module, but the current price is adequately competitive in the international market. International R&D




Source: International Energy Agency Photovoltaic Power Systems (IEA-PVPS)

Figure 4.5. Korean and International module price and international cumulative production




Source: IEA (2015)

Figure 4.6. International PV cumulative capacity in GW by the three scenarios

expenditures and PV module production are used for the 2FLC since new PV knowledge diffuses rapidly through the international market and the export-oriented Korean PV module industry is affected by international module production. International PV module production data from 1975 to 2013 was obtained from the Earth Policy Institute. The PV cumulative capacity in 2013 was 168 GW and has recently rapidly increased. The international R&D expenditure data from 1974 to 2013 was collected from International Energy Agency (IEA) statistics to measure the KS at the beginning of the PV R&D activity. The PV annual KS are calculated according to Equation (4) with varied depreciation rates of 5, 10, 15, 20% per year and 2 to 6 years of annual time lags. Therefore, the indexes of LBD and LBS are calculated with Equation (5), and the LDR and the LSR are obtained from Equations (2) and (3). Finally, the future Korean PV module price can be predicted with the most explainable LDR and LSR.

The future PV module price is anticipated with three future PV production scenarios, the Current Policies Scenario, the New Policies Scenario, and the 450 Scenario, which are forecasted throughout 2040 by the IEA (IEA, 2015). The predicted PV cumulative capacity in the three scenarios are presented in Figure 4.6. The Current Policies Scenario and the New Policies Scenario considers the policies and measures implemented as of mid-2015 that influence energy markets, and the 450 Scenario also takes into account relevant declared policy intentions with specific instruments that may not have been introduced yet.

Second, the future Korean PV LCOE is estimated. With the Korean PV module price predicted in the previous step, the future BOS is also observed for the LCOE analysis. The estimated future BOS cost is discussed by Jeong (2011) where the future BOS cost by 2031 is determined using a 16.7% LDR from 2001 to 2011. The data on the Korean PV annual production by 2029 was collected from the seventh Basic Plan for Long-term Electricity Supply and Demand (2015-2029), and the remaining annual production by 2040 was assumed to increase 7% from the previous year, which is the average increasing rate during the 5 years between 2025 and 2029. Finally, the annual PV system price ($I_t$) is determined by combining the PV module and BOS prices. The annual operations and maintenance expenditure ($M_t$) is estimated as 1% of the $I_t$ and the fuel expenditures ($F_t$) is considered to be “0” since the PV generation system converts sunlight directly into electricity. The discounted rate (r) is 5.5%, which is the social discounted rate used by the Korea Development Institute (KDI) that is applied to

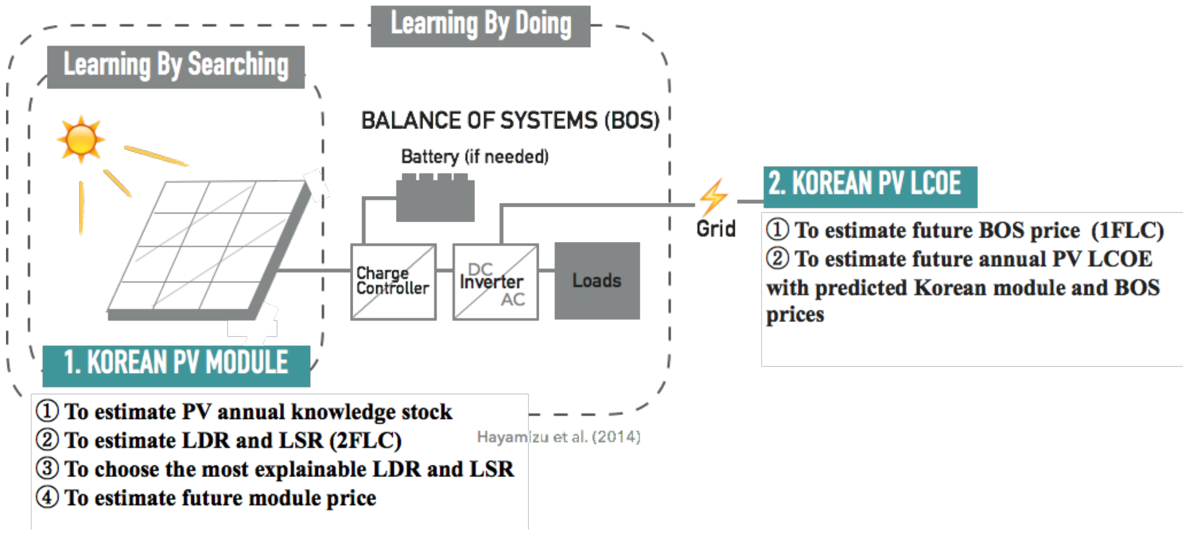



Figure 4.7. Described analytical framework

long-term projects or projects with long-term effects, such as a public investment. The economic life of a PV system is assumed 20 years (Lee et al., 2011). The annual PV generation ($E_t$) is estimated with Equation (7), as per Jeong (2011), with 0.7% of the degradation rate (d) and 15.5% of the capacity factor (CF), as follows:

$$E_t = (1-d)^t \times CF_t \times 8760 hours \times \text{capacity}. \qquad (7)$$

The Figure 4.7. shows the analytical framework to predict future Korean PV module prices and LCOE.

## 4.4 Results

This study uses the 2FLC and LCOE to predict the future Korean PV module and generation prices. The objective of the study is to determine if the price of a PV electricity system will reach the targeted PV generation prices by the given planned period presented in the Fourth Basic Plan for New and Renewable Energy.

### 4.4.1 Future PV module price in Korea

The KS was calculated in advance with scenarios of 2- to 6-year time lags and 5, 10, 15, 20% depreciation rates. The Durbin-Watson (DW) statistic and the variance inflation factor (VIF) tests were carried out to verify the serial correlation and multi-collinearity, respectively. The results, as estimated with OLS, are described in Table 4.2. Considering the adjusted $R^2$ is larger than 0.900, the DW is close to 2.000, and the VIF is below 10, an option with the CC and KS with a 5-year time-lag and 15% of depreciation is the most significant in explaining the Korean PV module price.

The indexes of LBD and LBS are specified as -0.188 and -0.159, respectively, as a result, and the LDR and LSR are estimated as 12.22% and 10.44% consequently through Equations (2) and (3). The future Korean PV module prices (2014 USD/W) predicted for 2040 according to the two learning rates and the three scenarios presented by the 2015 IEA World Energy Outlook are shown in Figure 4.8. The Korean PV module price is expected to decrease to USD 0.300/W in 2040 under the Current Policies Scenario, to USD 0.282/W under the New Policies Scenario, and to USD 0.264/W under the 450 Scenario.

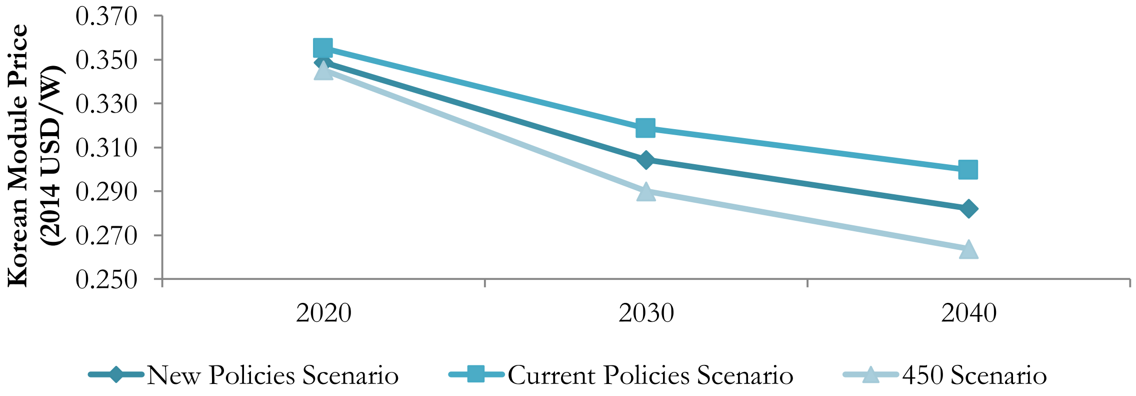



Figure 4.8. Future PV module price by 2035

Table 4.2. LDR and LSR results for the prediction of Korean PV Module Prices

| | | Cumulative Capacity | | | Intl' Knowledge Stock | | | Adj.$R^2$ | DW | VIF |
|---|---|---|---|---|---|---|---|---|---|---|
| TL | DR | Elasticity | T | LDR(%) | Elasticity | t | LSR(%) | | | |
| 2 | 5 | 0.176 | 2.001 | -12.97% | -0.043 | -7.768 | 2.94% | 0.899 | 0.893 | 4.658 |
| | 10 | 0.259 | 1.206 | -19.66% | -0.078 | -3.374 | 5.26% | 0.725 | 0.575 | 10.208 |
| | 15 | -0.136 | -0.415 | 9.00% | -0.041 | -0.922 | 2.80% | 0.563 | 0.320 | 15.027 |
| | 20 | -0.451 | -1.341 | 26.85% | 0.004 | 0.710 | -0.28% | 0.541 | 0.260 | 15.080 |
| 3 | 5 | 0.035 | 0.495 | -2.46% | -0.039 | -7.939 | 2.67% | 0.903 | 1.111 | 3.133 |
| | 10 | 0.024 | 0.179 | -1.68% | -0.071 | -3.758 | 4.80% | 0.749 | 0.776 | 4.536 |
| | 15 | -0.181 | -0.948 | 11.79% | -0.051 | -1.439 | 3.47% | 0.591 | 0.433 | 5.421 |
| | 20 | -0.341 | -1.727 | 21.05% | -0.021 | -0.495 | 1.45% | 0.548 | 0.300 | 5.246 |
| 4 | 5 | -0.055 | -0.099 | 3.74% | -0.038 | -9.340 | 2.60% | 0.925 | 1.437 | 2.303 |
| | 10 | -0.082 | -1.014 | 5.53% | -0.078 | -5.532 | 5.26% | 0.836 | 1.289 | 2.457 |
| | 15 | -0.166 | -1.470 | 10.87% | -0.091 | -2.956 | 6.11% | 0.697 | 0.931 | 2.581 |
| | 20 | -0.255 | -2.049 | 16.20% | -0.074 | -1.806 | 5.00% | 0.615 | 0.636 | 2.459 |
| 5 | 5 | -0.105 | -2.788 | 7.02% | -0.037 | -12.452 | 2.53% | 0.955 | 1.571 | 1.908 |
| | 10 | -0.152 | -4.083 | 10.00% | -0.087 | -11.721 | 5.85% | 0.949 | 1.632 | 1.672 |
| | 15 | -0.188 | -4.916 | 12.22% | -0.159 | -10.724 | 10.44% | 0.941 | 1.886 | 1.517 |
| | 20 | -0.226 | -5.388 | 14.50% | -0.214 | -9.138 | 13.79% | 0.922 | 1.913 | 1.385 |
| 6 | 5 | -0.094 | -2.550 | 6.31% | -0.037 | -12.870 | 2.53% | 0.957 | 1.538 | 1.962 |
| | 10 | -0.131 | -3.652 | 8.68% | -0.087 | -12.622 | 5.85% | 0.956 | 1.554 | 1.767 |
| | 15 | -0.157 | -4.159 | 10.31% | -0.164 | -11.483 | 10.75% | 0.948 | 1.684 | 1.652 |
| | 20 | -0.194 | -4.431 | 12.58% | -0.222 | -9.196 | 14.26% | 0.923 | 1.558 | 1.518 |

### 4.4.2 Future PV LCOE in Korea

Estimating the annual $I_t$ to measure the future, Korean PV LCOE requires two major expenditures, the PV module and the BOS. The expected BOS price by 2040 is shown in Figure 4.9, and is predicted to decrease to USD 0.64/W by 2040. The PV system price, which is the combined Korean PV module and BOS prices and the $M_t$ are presented in Table 4.3. Again, the annual $M_t$ is assumed to be 1% of the annual $I,$ and the $F_t$ is not expected to occur for this study.

Finally, the 2040 PV LCOE in Korea is measured under the IEA's three scenarios and the predictive values are as shown in Table 4.4. The figures from 2002 and 2013 are actual PV generation prices (Jeong , 2013), and the LCOE in 2020, 2030, and 2040 are forecasted according to the scenarios. The PV LCOE is predicted to continuously decrease to USD 0.011/kWh in 2040 under the most positive 450 Scenario.

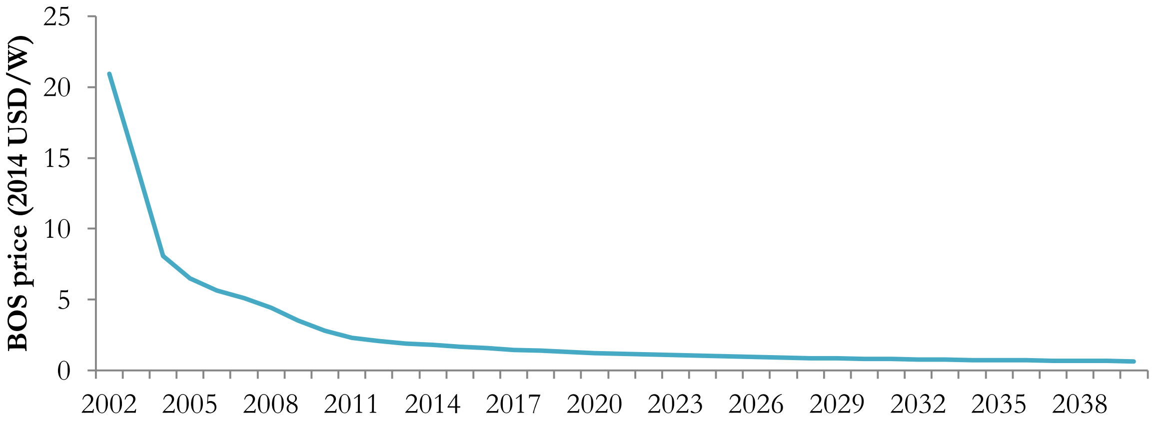



Figure 4.9. Korean BOS price by 2040

Table 4.3. PV system price ($I_t$) and operations and maintenance expenditures ($M_t$)

| | Korean PV Module and BOS prices ($I_t$) + Operations and Maintenance ($M_t$) (2014 USD/W) | | |
|---|---|---|---|
| 2002 | 27.82 | | |
| 2003 | 21.20 | | |
| 2004 | 12.41 | | |
| 2005 | 10.83 | | |
| 2006 | 9.77 | | |
| 2007 | 8.85 | | |
| 2008 | 7.49 | | |
| 2009 | 5.97 | | |
| 2010 | 5.05 | | |
| 2011 | 3.63 | | |
| 2012 | 3.02 | | |
| 2013 | 2.82 | | |
| | New Policies Scenario | Current Policies Scenario | 450 Scenario |
| 2020 | 1.60 | 1.61 | 1.60 |
| 2030 | 1.14 | 1.15 | 1.12 |
| 2040 | 0.37 | 0.39 | 0.34 |

Table 4.4. A prediction of the Korean PV LCOE by 2040

| | Korean PV LCOE (2014 USD/kWh) | | |
|---|---|---|---|
| 2002 | 1.189 | | |
| 2003 | 1.158 | | |
| 2004 | 0.913 | | |
| 2005 | 0.684 | | |
| 2006 | 0.643 | | |
| 2007 | 0.615 | | |
| 2008 | 0.550 | | |
| 2009 | 0.476 | | |
| 2010 | 0.385 | | |
| 2011 | 0.261 | | |
| 2012 | 0.286 | | |
| 2013 | 0.262 | | |
| | New Policies Scenario | Current Policies Scenario | 450 Scenario |
| 2020 | 0.252 | 0.253 | 0.251 |
| 2030 | 0.096 | 0.098 | 0.095 |
| 2040 | 0.012 | 0.013 | 0.011 |

### 4.4.3 Sensitivity Analysis

Sensitivity analysis is necessary when there are uncertainties in the variables used for analysis. The sensitivity analysis for the Korean PV module price was performed in advance. Based on Hayamizu et al. (2014), this study applies ±5% annually to the baseline value of international R&D expenditures to observe the R&D impact on capital costs of PV modules by 2040 and estimate PV module prices in each scenario. The results are shown in Figures 10, 11, and 12. The PV module price will likely decrease to USD 0.231/W by 2040 under the 450 Scenario with the R&D expenditure having increased 5% annually from 2014.

The PV LCOE is also re-estimated with the PV module prices changed according to the sensitivity analysis. The results of the changed PV LCOE are shown in the Table 5.The PV LCOE is expected to drop to USD 0.010/kWh by 2040 under the 450 Scenario with the R&D expenditures having increased 5% annually, or at least USD 0.014/kWh under the Current Policies Scenario with the R&D expenditures having decreased 5% annually

Doshi et al. (2011) and Jeong (2013) apply ±30% to the baseline values of the capacity factor (CF), discount rate(r), economic lifetime of system(n), depreciation rate(d), and other variables to conduct sensitivity analysis. This study also conducts sensitivity analysis by applying ±30% to the baseline values of the parameter variables. The results that describe changes in the PV LCOE are shown in Table 4.6. The CF and I impact the Korean PV LCOE significantly, as the LCOE decreases by 23.33% and 30% as the CF improves by 30% and the I decreases by 30%, respectively. Therefore, the LCOE decreases by USD 0.00678/kWh when the I declines 30% from the expected price, and USD 0.007497/kWh when the CF improves 30% from the assumed performance of 15.5%.

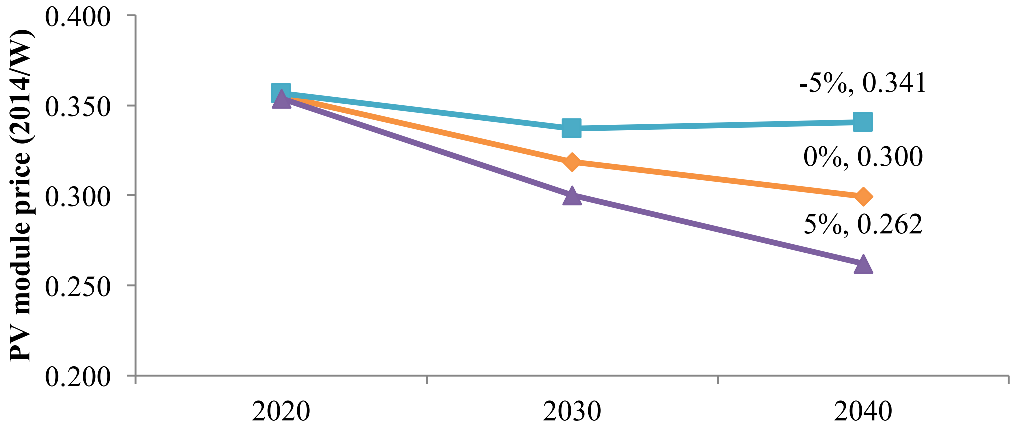



Figure 4.10. Sensitivity analysis of the PV module price under the Current Policies Scenario

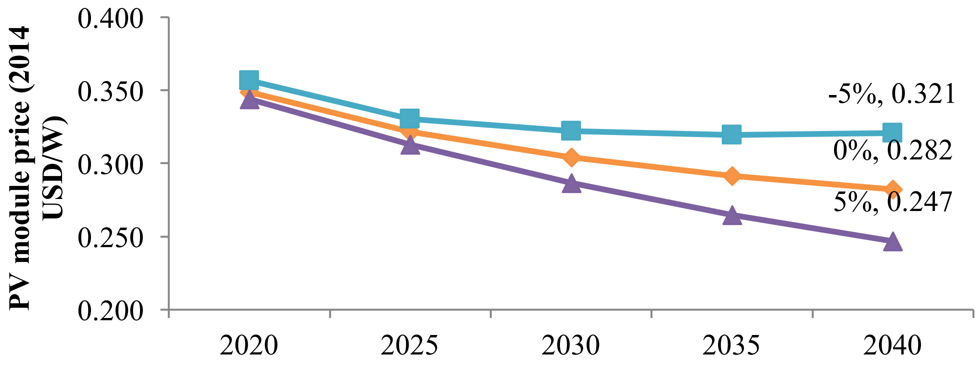



Figure 4.11. Sensitivity analysis of the PV module price under the New Policies Scenario

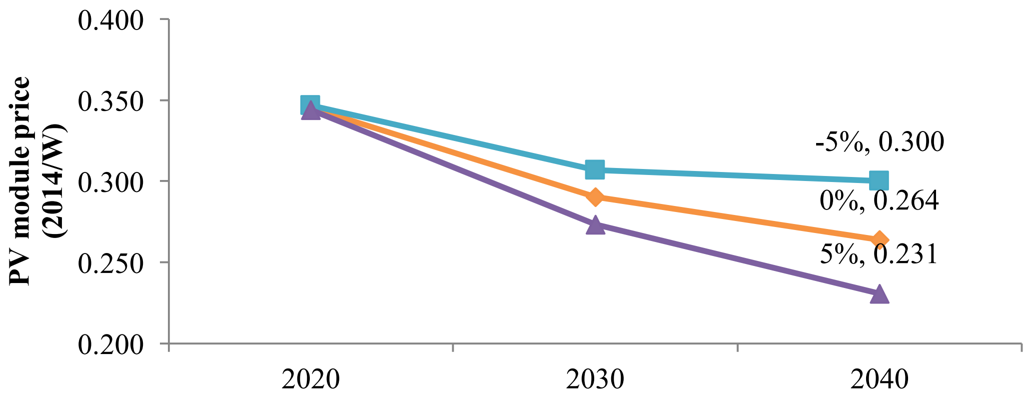



Figure 4.12. Sensitivity analysis of the Korean PV module price under the 450 Scenario

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Table 4.5. PV LCOE according to the sensitivity analysis of the Korean PV module prices

| | PV LCOE (USD/kWh) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | New Policies Scenario | | | Current Policies Scenarios | | | 450 Scenarios | | |
| | -5% | 0% | 5% | -5% | 0% | 5% | -5% | 0% | 5% |
| 2020 | 0.253 | 0.252 | 0.251 | 0.253 | 0.253 | 0.253 | 0.252 | 0.251 | 0.251 |
| 2030 | 0.098 | 0.096 | 0.095 | 0.099 | 0.098 | 0.096 | 0.097 | 0.095 | 0.094 |
| 2040 | 0.013 | 0.012 | 0.010 | 0.014 | 0.013 | 0.011 | 0.013 | 0.011 | 0.010 |

Table 4.6. Sensitivity analysis of the Korean PV LCOE in 2040

| | -30% | +30% |
|---|---|---|
| Economic life of system (n) | -1.44% | 1.24% |
| Discount rate (r) | 0.35% | -0.33% |
| Capacity Factor (CF) | 42.86% | -23.33% |
| Depreciation rate (d) | -1.79% | 1.38% |
| Investment expenditure (I) | -30.00% | 31.79% |

## 4.5 Conclusion

This study estimates the future Korean PV module and LCOE prices by 2035 to verify if the forecasted prices will reach the national targeted generation prices with the current level of production and R&D support. First, the Korean PV module price is projected with a 2FLC, taking into account international PV cumulative production and R&D expenditures. As a result, the PV module price has a tendency to decrease by 12.22% of the LDR and 10.44% of the LSR every time the cumulative PV production and KS are doubled. The time lag and depreciation rate for the PV R&D are measured as 5-year and 15%, respectively, and have an adjusted $R^2$ of 0.941, DW of 1.886, and a VIF of 1.517. These results indicate that 5 years are required between R&D investment and the realization of quantifiable benefits, since the price and KS of the technology depreciates rapidly at 15% annually, which is characteristic of an evolving technology such as PV.

Forecasting the PV electricity price in Korea is based on the LCOE formula sequence. The PV generation price is estimated to decrease to USD 0.011~0.013/kWh by 2040. The PV target generation price, according to the Fourth Basic Plan for New and Renewable Energy released in 2014, is expected to reach KRW 245.75/kWh by 2017, KRW 117.6/kWh by 2022, and KRW 60.9/kWh by 2035. The annual PV LCOE prices are estimated with the constant average annual growth rate (CAAGR) to determine if the PV LCOE would decrease by its expected target price. The CAAGR tends to be higher with time as well, as do the New Policies Scenario and 450 Scenario.

As shown in Table 4.7., the PV generation price is not expected to reach the 2022 goal, but will decline to KRW 60.9/kWh of the 2035 PV target price by 2032 and decrease to KRW 31.043 ~ 39.917/kWh by 2035. According to the sensitivity analysis performed due to the uncertainty in the variables used for the analysis, the price is expected to change with CF and I, which is required to enhance the efficiency of PV modules and reduce system costs. As for the time to reach the grid parity for PV, it is not anticipated to be lower than the Korean System Marginal Price (SMP) by 2022 according to a scenario provided by the Korea Power Exchange (KRX). The SMP in 2022 is expected to be KRW 127.1/kWh (Jeong , 2013), and the PV generation price will reach the grid parity before 2025-26 if the SMP maintains this level.

This research uses international PV production and R&D investment to estimate the LDR and LSR of Korean PV. The PV modules produced in each country are being sold

Table 4.7. Korean target PV generation price and expected PV LCOE price

| Target PV Generating Price (KRW/kWh) | | | | | | |
|---|---|---|---|---|---|---|
| | 2017 | 245.75 | 2022 | 117.6 | 2035 | 60.9 |
| Expected PV LCOE Price (2014 KRW/kWh) | | | | | | |
| | -5% | | 0% | | 5% | |
| | Price | CAAGR(%) | Price | CAAGR(%) | Price | CAAGR(%) |
| Current Policies | | | | | | |
| 2017 | 280.494 | 2020-2030 | 280.349 | 2020-2030 | 280.204 | 2020-2030 |
| | | -1.67 | | -1.68 | | -1.69 |
| 2022 | 221.091 | 2030-2040 | 220.179 | 2030-2040 | 219.259 | 2030-2040 |
| | | -8.95 | | -9.10 | | -9.25 |
| 2035 | 39.917 | 2040-2050 | 36.833 | 2040-2050 | 33.891 | 2040-2050 |
| | | -17.50 | | -18.55 | | -19.63 |
| New Policies Scenario | | | | | | |
| 2017 | 280.494 | 2020-2030 | 279.716 | 2020-2030 | 279.205 | 2020-2030 |
| | | -1.67 | | -1.7 | | -1.78 |
| 2022 | 220.506 | 2030-2040 | 218.752 | 2030-2040 | 217.362 | 2030-2040 |
| | | -9.07 | | -9.2 | | -9.36 |
| 2035 | 38.219 | 2040-2050 | 35.285 | 2040-2050 | 32.484 | 2040-2050 |
| | | -17.99 | | -19.0 | | -20.11 |
| 450 Scenario | | | | | | |
| 2017 | 279.487 | 2020-2030 | 279.346 | 2020-2030 | 279.205 | 2020-2030 |
| | | -1.76 | | -1.77 | | -1.78 |
| 2022 | 218.545 | 2030-2040 | 217.695 | 2030-2040 | 216.837 | 2030-2040 |
| | | -9.19 | | -9.33 | | -9.47 |
| 2035 | 36.484 | 2040-2050 | 33.70 | 2040-2050 | 31.043 | 2040-2050 |
| | | -18.54 | | -19.58 | | -20.64 |

in the domestic and international markets, indicating that the price of Korean PV modules is determined based on the demand and supply in the international open market. Therefore, while PV modules from other countries, such as China, are less expensive, Korea should strengthen its domestic PV technology to be able to sell its PV modules in the international market. In fact, the current market price of c-Si PV does not differ much between countries since the PV knowledge accumulated by past R&D activities in advanced countries, such as Europe or Japan, is rapidly diffused globally through the products, and China is leading the market by having a second mover advantage.

Knowledge creating activities, such as R&D, struggle from three types of market failure: indivisibilities, uncertainty, and externalities. These market failures reduce the incentive to invest in R&D. R&D projects involving significant fixed costs exhibit economies of scale with highly educated human resources or specified use (indivisibilities); it can be uncertain if a project will have market value (technological uncertainty); and, moral hazard generates difficulties in carrying out R&D activities (externalities).

In addition, knowledge-creating activities, as a public good, are both non-rival and non-excludable (Geroski, 1995). The knowledge can be in circulation to be consumed by many people, which weakens any attempt to produce new knowledge (non-rival); and, it is difficult for innovators to value the knowledge created and exclude its use by others (non-excludable), which also reduces the innovator’s R&D efforts. However, often those who heavily invest in R&D activities benefit since the knowledge is seldom worthless, and foreknowledge enables a private rate for individuals who invested in R&D that exceeds the social rate of return as the first runner in the market.

New PV technology should be developed with R&D to become a front-runner in the market. In fact, the current major source of PV income in Korea is from export revenue, mostly in the polysilicon industry in an upstream value chain that has a high entry barrier and is being operated by large companies with a large international market share. On the contrary, the downstream of the PV value chain that relies largely on export revenue due to the narrow domestic market suffers from its limited position in the international market. This is predicted to get more difficult in the long-term due to the lack of past performance and verification of product reliability through commercialization.

It is important for innovative PV to have opportunities to evolve to produce large quantities, improve cost competitiveness, and occupy a dominant position in the international market. The technological gap between the future generation of PV, such as PV based on thin-film technology, and the technology level in advanced countries is seriously widening. Specifically, in 2011, Korea was 66% compared to advanced countries, and the localization rate was also low at 46%.

To enhance the R&D for new PV technology, which is expected to decrease PV module and PV generation prices, strong, short-term R&D investment in c-Si of low cost and high efficiency is required. This will distinguish the technology from advanced countries, enlarge the domestic market by strengthening diffusion policies, such as RPS, promote the use of domestic products, and accumulate track records so they can be sold in the international market. Further, strong R&D investment in future PV technology, such as a-Si and CIGS, will enhance its technological level to allow it to dominate the market share in the long run. Such investments will fund in-depth and durable evaluations of R&D projects until the PV modules have economical value through commercialization.

# 5 Conclusion

Korea is the 8th largest energy consuming country that uses 1.56% of the world energy and consequently is one of the biggest emitters of greenhouse gases (GHGs) that influence on climate change. In addition, the energy security has been also a major political issue in the country that is heavily dependent on overseas' fossil fuels as well as nuclear power that is controversy in use owing to the safety and environmental concerns on the power plants, particularly growing after the 2011 Fukushima power plant accident in Japan.

Therefore, with increasing significant matters on climate change and energy security, the infinite and clean renewable energy technology has been newly introduced in Korea as one of effective solutions in dealing with these challenges and contributing to the economic development. “Low Carbon and Green Growth” was proclaimed as the nation's vision in 2008 and the 4th Basic Plan for the Promotion of the Development, Use and Diffusion of New and Renewable Energy (2014~2035) has been implemented since 2014, aiming at increasing the use of renewables to 11% of Total Primary Energy Supply (TPES).

Various activities with regards to research and development (R&D) that creates and produces new knowledge are crucial and essential for the economic growth. While R&D activity requires a lengthy period of time and a financial investment in labour force and technological device that are normally pricey, only few outcomes of R&D that are successfully designed and developed to acknowledge their commercial value in the market can be called finally as an innovation. In addition, each innovation shows the different degree of adoption, and the characteristics of relative advantage and compatibility in innovation are crucial to differentiate the newly introduced innovation from the existing idea that is expected to replace with the innovation.

The scale of Korean R&D investment for renewables has been increased by KRW 63,734 million in 2014 that accounts for 4.3% as a percentage of GDP and presents the highest percentage of the year among OECD countries. However, the efficiency of R&D productivity in the renewable technology is required to be improved further. While the R&D investment in renewables continues to grow, Korean energy consumption by renewables accounts for only 4.4% as a percentage of TPES in 2014. Furthermore, Korean renewable technology should be enhanced to be more competitive so that the technology can occupy largely the international market share in the long run.

Research objective of the current dissertation seeks to assess the R&D efficiency in Korean renewable energy technology and changes in price of the technology with quantitative method. The productivity of R&D investment in Korea renewable energy technology is evaluated, considering distinct R&D performers and technological phases whose characteristics and purposes of carrying out R&D activities vary. In addition, future price of photovoltaic (PV) technology that has received the largest R&D support is selected to forecast its future price with an impact of R&D to inquire if the energy will reach its target price by 2035 stated in the "2nd National Basic Plan for Energy" and have an ability to compete conventional energy sources in the energy market.

In Chapter 3, Data Envelopment Analysis (DEA) is used to estimate the efficiency of R&D productivity among 1340 national R&D projects in renewable energy technology in Korea by performer and by technical progress phase. The R&D projects are classified by levels of technical progress phase (basic, applied, and development) as the first step to satisfy the homogeneity condition, and the result of efficiencies are averaged by performer.

The result explains that one of the reasons why the industry development in renewable energy is not growing fast is that large firms' R&D productivity in the renewable energy technology is low. In fact, the large firms are proved to have several benefits in performing R&D compared to smaller firms, in spite of some weakness such as inflexible bureaucratic R&D management, and expect to have more fruitful results in outputs than another performer.

While the efficiencies on basic and applied research are rather high in most performers because direct outputs from R&D support are sufficiently created, most research on the development phase correlated to profitability performed mostly by firms are rather inefficient. This is because its economical outputs compared to initial R&D support are inadequately produced, though those performers are expecting R&D results with economic value. In addition, the efficiencies on the development phases show the efficiency in the smaller firms is slightly higher than large firms that received the R&D support the most in amount as well as per project.

Chapter 4 shows that the future Korean PV module and Levelised Cost of Electricity (LCOE) by 2035 to verify if the forecasted prices will reach the national targeted generation prices with the current level of production and R&D support. First, the Korean PV module price is projected with 2 Factor Learning Curves (2FLC), taking into account international PV cumulative production and R&D expenditures. As a result, the PV module price has a tendency to decrease by 12.22% of Learning by Doing Rate (LDR) and 10.44% of Learning by Searching Rate (LSR) every time the cumulative PV production and Knowledge Stock (KS) are doubled. The time lag and depreciation rate for the PV R&D are measured as 5-year and 15%, respectively.

Forecasting the PV electricity price in Korea is based on the LCOE formula sequence. The PV target generation price, according to the Fourth Basic Plan for New and Renewable Energy released in 2014, is expected to reach KRW 245.75/kWh by 2017, KRW 117.6/kWh by 2022, and KRW 60.9/kWh by 2035. The anticipated PV LCOE is not expected to reach the 2022 goal, but will decline to KRW 60.9/kWh of the 2035 PV target price by 2032 and decrease to KRW 31.043 ~ 39.917/kWh by 2035.

The research shows the R&D activities concerning renewables have been actively carried out in Korea and will positively affect national critical issues of energy security and economic development and handle global climate change. Accordingly, the strong and adequate allocation of R&D investment by technologies and performers and a thorough and in-depth evaluation of before-and-after R&Ds are key to improve the R&D productivity. Securing industrial competitiveness in the overseas renewable energy market is necessary through more efforts into R&D focused on the core technology.

For the purpose of expanding the market share, smaller firms that possess unique R&D on the diversity of projects are able to play an important role, which also enables them to coexist with large firms. Therefore, it is desirable for the government to encourage more knowledge and technology sharing between smaller and large firms for mutual growth by localizing the renewable energy technology and further broadening markets overseas. In addition, the innovative technology like renewables needs a consistent and long-sighted policy establishment for performers to anticipate the future.

With increasing issues on climate change and energy security, the infinite and clean renewable energy technology would be a solution on handling these challenges with an economic development. Firms' R&D productivity of the renewable energy technology is low while the renewable technology on development phase performed by firms, especially large firms, anticipates generating the economical outcome in the short term. PV price will reach its national target price that would be competitive against the price of conventional fossil fuels in 2035 if the current level of diffusion and R&D supports are given to the technology.

It is needed to review whether the R&D investment and labors are made only according to the firm size rather than a consideration that the firm's business unit per se has an ability to make a result of the R&D carry to the real commercialization. Both ex-ante and ex-post analysis to understand firm's ability to complete R&D activity and to assess the R&D activity terminated are more strictly required to enhance R&D productivity. Smaller firms that possess unique R&D on the diversity of projects are able to play an important role, which enables also them to coexist with large firms.

The R&D effort in the new type of technology should continue for Korea in order to lead the market as a front-runner's position with the advanced level and price competitiveness of the technology. It is difficult for innovators to value its knowledge created and they do not preclude its use by another, which also reduces innovator's efforts in R&D activity. However, we often see those who heavily invest in R&D activities benefits from them since the knowledge is seldom to be sold costless and foreknowledge enables the private rate of return in the individual to have invested in R&D exceeds its social rate of return as the first runner in the market.

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# Acknowledgement

Most of all, I would not have completed my study without my family's dedicated assistance. While I was apart from Korea for nearly 6 years, they devotedly helped their dearest daughter and sister only concentrate on study. I really appreciate my family and promise to return their favour in the future. I love you!

Needless to say, I am extremely grateful to Usami sensei. His positive words and encouragement was valuable and essential for a student who had a hard time on completing her own study. I thank also for all his supports that enables me successfully settle in Korea as a researcher in an institute that I have longed for. I feel also appreciated Mishima-san for her consideration and kindness. She fulfilled as an another Lee after I returned to Korea. I am thankful to all members including Hirata-sensei in Usami's lab. I hope everything will come out all right with you.

Last, thanks everyone who supports, encourages, cheers, and comforts me until the end of this long and lonely study. I appreciate all my friends I met in Japan who are like an oasis in the desert, especially Reiko, Marie and her family, Imaeda-sensei and my Korean friends including Yang Soyoung and her family, Kim Soyoung and Yongwoo. I hope we will keep in touch now and for ever. Of course, I think my friends in Korea know how much I thank them. ☺

皆さん、本当にありがとうございました。