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Role of Innovation, Technology Diffusion and Policies for Sustainable Growth

- Empirical analysis of energy-use and renewables technology -

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Abstract

Role of Innovation, Technology Diffusion and Policies for Sustainable Growth

-Empirical analysis of energy-use and renewables technology-

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In recent times, investment for developing clean energy technologies is increasing rapidly. However, private R&D investment in this field may be lower than the social optimal level owing to market failures from environmental (e.g., lack of significant pricing policies for GHG emissions) and knowledge (e.g., free-riding by the public-good nature of new knowledge) externalities. To solve these issues and bring forth national innovations, several governments have implemented various technology-push and market-pull policies.

The goal of this thesis is to identify the social phenomenon, that is, the market failure-energy efficiency paradox, and assess the impact of government policies on the process of domestic technological change and the foreign competitiveness of clean energy technology, through empirical analyses using a variety of techniques. This thesis is carried out in three parts.

First, this thesis analyzes the market failure phenomenon of about 43 countries' energy-saving technologies using a non-parametric methodology. Specifically, each country's country-specific CO_2 emission trend is investigated, and the impact of changes in technical efficiency and technological innovation on CO_2 emissions is evaluated using an originally developed production-based decomposition method. This analysis enables us to identify quantitatively the market failures of various energy-saving technologies, that is, the energy efficiency paradox phenomenon (stagnated diffusion in energy-efficient technologies).

The results show that despite national variation in technical efficiency and innovation capacity, the effect of market failure in Northern Europe, Western Europe, North America, South Korea, and Japan is less than that in other regions, and a number of OECD countries have tried to strengthen their capacities and absorb foreign technologies since 1998 when the Kyoto protocol was introduced. This indicates that when technological advances are made, clean energy technologies do not diffuse naturally, namely, by the simple logic of the market, but are spread following certain international regulations such as the Kyoto protocol, and take place with the continued support for national technology diffusion.

Therefore, it is important to find an efficient strategy to harmonize support policies, for which the impact of the policies from various perspectives need to be evaluated. The second research topic is an empirical determination of a domestic innovation system, which consists of three stages, that is, the invention-innovation-diffusion stages, based on the Schumpeter theory, and the interactions in this endogenous technological change system. The empirical analysis is conducted as a panel analysis of the OECD countries' renewable energy technologies, that is, their solar PV and wind power technologies, for the period 1991–2007.

In addition, this thesis determines the static impact of the government's renewable energy policies, which are classified into five—public R&D, tariff incentives, renewable energy obligations, environmental taxes, and public investment—on each stage of the system. The static impact of the policies enables us to estimate the direct and fixed effect of the policies on each stage, because the interactions between the three stages are not considered, giving us an accurate assessment of the policies. Furthermore, as the dynamics of the policy impacts that form in a virtuous cycle are simulated, one can evaluate the total impact of the policies under the interactions between the three stages.

According to the empirical results, the virtuous cycle is formed between the invention-innovation-diffusion stages and the static impact of policies varies according to the renewable energy technologies. In particular, public R&D plays a key role as a support measure motivating innovation. The results of the policy dynamics show that public R&D and tariff incentives have a positive impact on the three stages in the system. In addition, this thesis confirms the view that competition-inducing instruments would play an increasingly important role, as the renewable energy technologies develop further. (Environmental taxes appear to play a positive role in innovations within wind power with highly competitive pricing.)

Third, as the renewable energy technologies become the driving force for sustainable economic growth through international trade, it is also important for us to identify the interrelationships between domestic innovations and international trade, and evaluate the impact of the policies on international trade. Therefore, this thesis builds a model to investigate the interactions between domestic innovations and export and import, and determines the effects of the renewable energy policies enumerated above on exports and imports.

The results underline the fact that as the renewable energy technologies develop and become more advanced, the dependence of R&D activity on international trade becomes higher, and any further domestic R&D and technological diffusion would lead to increased exports. Specifically, technological development enables the technology with high potentials to improve cost-competitiveness and strengthen foreign competitiveness; however, market factors dominate the technology with low potentials. In terms of policy impact, the renewable energy obligation to promote a competitive policy has a positive impact on solar PV trade, while tariff incentives have a positive impact on wind power.

From the empirical results and the foregoing implications, this thesis proposes a harmonization strategy as follows: the instruments for technology-push such as public R&D and tariff incentives should be made compulsory for both solar PV and wind power. With the use of technology, the policy makers should introduce different competition-inducing instruments, for example, renewable energy obligations for solar PV and environmental taxes for wind power. When the technologies are more competitive and the utilities' right to choose a clean energy technology is more strengthened, it would be necessary to consider the competition system by technology. In other words, the renewable energy obligations should be complemented specifying a quota by technology, because until now, environmental taxes have not shown a positive impact on the sustainable growth of solar PV. This thesis would therefore emphasize that the target of policies should be adjusted by technologies, and policies should be diversified for a symmetric development of renewable energy technologies.

The significance of this thesis is that it provides quantitative evidence for the existence of country-specific market failures using novel decomposition techniques. In addition, the novelty of this thesis is that it divides the sustainable growth model for renewable energy into a domestic innovation and international trade model, and assesses the long-term dynamics of policy impacts as well as the static impact of policies. This thesis therefore lays the foundation to analyze the policy impacts from a variety of perspectives.

Keywords: energy efficiency paradox, energy-use technology, endogenous technological change system, renewable energy policies, international trade, sustainable growth

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Chapter 1. Overview

1.1 Research Background

Since clean energy technologies, including energy saving and efficiency improvement technologies, and renewable technologies not only supply pollution-free energy but also form a new growth engine for sustained economic development, many countries are presently rushing to develop the renewable technologies. Especially from the late 1990s to the mid-2000s, the developed countries are charged with a differentiated burden—reducing their domestic GHG emissions by forming regulations and consensuses about global action for climate change. This has resulted in a wide domestic deployment of these technologies, and increased R&D investments for the development of advanced technologies.

For example, the installation of major renewable energy facilities has rapidly grown in the world, and their current growth rate exceeds the required annual growth rate of 2020 (IEA, 2011a). For public R&D investment, although there are national variations, the share of renewable energy technology in the total energy R&D is stable, averaging 7.6% until 2006; recently, the share is seen increasing (IEA, 2006; IEA, 2011b).

Nevertheless, private R&D effort and investment in clean energy technologies are poor owing to market failures because of the effects of environmental and knowledge externalities (Jaffe et al., 2005). The market failures caused by environmental externalities refer to the non-market costs for pollutant abatements for cleaner renewable energy, resulting in firms investing in them at a less-than-socially optimal level (Jaffe et al., 2005; Popp, 2006; Pizer and Popp, 2008). In addition, the spillover from other firms' experience or knowledge coming from the public-good nature of new knowledge allows companies to enjoy a free ride (Jaffe et al., 2005).

Furthermore, even if cost-effective technologies are developed, they are not diffused, or diffused only gradually, due to the above externalities and path-dependence issues. Jaffe and Stavins (1994a) referred to this phenomenon as an energy efficiency paradox (or energy paradox), which can also be expressed as a stagnation in the spread of energy-efficient technologies. In fact, despite substantial improvement in the efficiency of energy use technologies, the adoption of these technologies is slow due to market structure, finance, and information barriers (IEA, 2011a).

The energy efficiency paradox, a major attribute of the diffusion process in clean energy technology, occurs from potential market failures and/or firm's characteristics, and forces governments to intervene in the market of these technologies with various plans and policies (Jaffe and Stavins, 1994b; Almeida, 1998; DeCanio and Watkins, 1998; Kounetas and Tsekouras, 2008). Jaffe and Stavins (1994b) found this phenomenon occurring largely owing to two factors, potential market failures (e.g., information problems, nonfulfillment of relevant agencies, and unobserved costs) and other factors (e.g., individual information costs, higher depreciation rates, and heterogeneity of firms). They clarified that whether government policy intervention would be needed will depend on the type of causes. Almeida (1998) emphasized the need for government intervention to improve technology diffusion and market structure, because the market forces will inhibit the diversification of trade and lowered incentives will reduce the application of efficient technologies. Therefore, the government should impose various incentives and regulations to correct market failures, and thereby help the development and diffusion of clean energy technologies.

Specifically, in the early stage, the government should concentrate on creating demand for the technologies, and gradually devote itself to establishing an innovation environment for the natural technological progress and advanced competitiveness. Following Romer (1990), innovation can be regarded as the engine for sustainable economic growth, which would thereby increase the overall returns to scale. However, innovation cannot be created by itself but needs to be formed as an organized activity—that is, through innovation-push (a supply perspective) and innovation-pull (a demand perspective) activity. Therefore, for successful technological innovations, rather than a fragmentary view, the entire of endogenous technological change process must be considered. This means that in order to evaluate policy potentials and resolve the energy paradox and the underinvestment issue in clean energy technology, the impact of the policies on the entire process of technological progress must be understood, because the policy impacts can differ by progress stage (Jaffe et al., 1999).

While there are a variety of views on the process of technological progress, Schumpeter (1934) suggested that the degree to which a technology will change and become widely used depends on three conditions, that is, the invention stage, the innovation stage, and the diffusion stage.

The first stage of technological change is invention, which refers to new knowledge, primarily achieved through R&D. Invention has the potential to develop economically and commercially feasible products, that is, through innovation (Popp, 2005), leading eventually to the generation of profit (Jaffe, 1986). Therefore, inventions come because of R&D activity, and the consequent increase in knowledge triggers innovations.

Innovation, the second stage, adds economic value to the invention stage, and optimizes it for the market. Through innovation, a firm can produce dynamic profits by utilizing all its opportunities, including exploiting the new market, changing production designs, operational improvement, and technological progress.

The last stage is diffusion; this stage indicates the level to which a technology can be adopted in the market and is based on the market size and technological potential. Diffusion plays a key role in endogenous technological change, adding market opportunities and learning effects to the invention and innovation stages.

These stages are not independent, but interrelated with one another through learning effects and systematic market expectations, and one should not just consider the interactions among the stages but also estimate the impacts of government policies on the interaction systems.

In order to establish an early market and further create endogenous technological systems, the government often tries to introduce appropriate policies in each stage. In practice, such policies play a significant role in promoting R&D investments and improving market conditions. First, the governments' technology-push policies support R&D activity and technological progress, and their direct support measures, such as public R&D, and indirect measures, such as private R&D subsidies, are helpful in resolving technological uncertainty. If the technology level and market are not fully developed, the role of the government becomes more important.

Second, to expand the market size, the governments have intervened primarily through tax-based instruments, infrastructure support, public investment, financial support, and so on. For example, Germany has set a 20% target to increase its energy efficiency by 2020, and introduced supporting subsidies, low-interest loans, and GHG-reduction regulations. For renewable energy, many European countries have used price-based instruments, guaranteeing a premium price for renewable electricity generation, while other countries, including the United States, the United Kingdom, and Japan, employ quantity-based instruments, enforcing renewable energy targets and allowing tradable certificates. Some European countries, including Denmark, Finland, and Netherlands, have imposed CO_2 emission or fossil fuel taxes on conventional electricity, or have given tax exemptions to users of renewable electricity (IEA, 2004).

Nowadays, the harmonization of various policies is becoming more and more important, with lively discussions on the optimized and efficient attainment of GHG-reduction goals. Additionally, achieving the targets for economic growth and GHG emission reduction at lower costs has become a critical issue (Menanteau et al., 2003). In practice, the European Commission has tried to reinforce such support schemes further and to bring about their harmonization (Lauber, 2004). For harmonization of the policies, before assessing the performance of renewable energy-related policies over the complete technological change system, consideration of the various learning effects from the invention stage to the diffusion stage is required. The accurate examination of the policy impacts will enable the efficient resolution of market failures and, furthermore, help the policy makers to plan an appropriate road map for a sustainable economic development under the national conditions.

1.2 Research Objectives

The objectives of this thesis are to assess the impact of the clean energy technologies on the environment and provide the policy makers with policy implications for a sustainable development. To achieve this, the thesis focuses on two representative technologies, the energy-use technology and the renewable energy technology, which are growing rapidly, and are expected to have a large potential for reduction in green-house gas (GHG) emissions (IEA, 2011a).

Specifically, energy-use technology is considered to assess the environmental impact of clean energy technology, because it shows the typical market and diffusion characteristics of clean energy technology. The IEA (2011a) has pointed out that since 1990, efficiency improvement in the energy-use technology in the industrial sector has not been remarkable, and even the diffusion of efficient energy-use technologies is slow owing to market barriers and the lack of information and certification institutions.

To identify the innovation systems and find policy implications, I examine the renewable energy technologies based on a variety of policies available in the literature. The renewable energy technologies have grown tremendously through various government support policies (IEA, 2011d), which have contributed to technology development, industrial growth, and market expansion (OECD/IEA, 2003). This will help one identify the interrelations between the policies and innovation systems. Furthermore, it is appropriate to evaluate the role of policies by their characteristics, because the renewable energy policies show heterogeneous characteristics (e.g., price-based, quantity-based, and tax-based characteristics) by their support scheme.

1.2.1 Environmental assessment

This thesis starts with a question: how can one find evidence of market failure in clean energy technology? Although the literature contains lively discussions and substantial theoretical bases on market failure and the energy efficiency paradox (Jaffe and Stavins, 1994a; DeCanio and Watkins, 1998; Jaffe et al., 2005; Popp, 2006; Pizer and Popp, 2008), it is difficult to find empirical evidence, because the process from technological change to technological diffusion is not observable. Therefore, in almost studies, the energy efficiency paradox is regarded as a conceptual issue, and they have attempted to resolve the issue through simulations based on the optimal behavior scenario rather than empirical analysis.

Before examining the innovations and policies in clean energy technology, this study would first empirically assess the environmental impact of clean energy technology. Specifically, I analyze the worldwide carbon dioxide (CO_2) emission trends and the underlying factors creating them. In addition, I concentrate on the impact of changes in technical efficiency and the technological progress of energy-use technology on CO_2 emissions to assess each country’s relative effort toward emission mitigation, and try to find temporal changes in the relative degree of the energy efficiency paradox in each country.

This analysis of technological impact on the environment and the energy efficiency paradox lays out a logical basis for why I construct the technological progress from the development of technology to its diffusion and evaluate the policy impact over the system, because this efficiency paradox will allow the government to intervene from the development of technology to the market expansion stage.

1.2.2 Innovation and policy

In addition to obtaining empirical evidence for the market failure of clean energy technology, this study examines the process of endogenous technological change in clean energy technology and the government's role in promoting the system. In particular, this study is noteworthy for examining the role of R&D, which supplies an innovative resource for domestic technological diffusion and furthermore absorbs foreign technologies and increases global competitiveness through international trade.

This thesis models the process of endogenous technological change on the basis of the learning effect, and empirically analyzes the dynamics of the government policy impacts on the system in the case of renewable energy. Specifically, the purpose of this study is to determine empirically the following two matters: *an innovative strategy for domestic technological diffusion,* and *an innovative strategy for sustainable growth with international trade*.

First, to determine a domestic innovation system, I decompose the technological change system into three component stages, that is, the “invention” stage, the “innovation” stage, and the “diffusion” stage, and investigate the interactions between these stages. It is important to identify the various learning effects that occur in this system, because these effects may distort policy impacts. Then, I evaluate the performance of the policies on each stage from the interactions between the stages (i.e., static impact of policy), and simulate the long-term dynamic impacts as the stages interrelate in a virtuous cycle.

This study also provides the empirical basis to optimize the policies for renewable energy technologies with different development levels. In addition to comparing the policies, I evaluate the impact of international knowledge spillover on the technology changes, and from this, find a link between technological development and international knowledge transfer.

Second, this study expands the system of domestic innovation into a sustainable innovation system with foreign competitiveness. I establish the interrelations between the domestic innovation system and international trade with endogenous R&D activity and technological diffusion, and determine the role of renewable energy policies in the system. The renewable energy policies focus on domestic innovations and the diffusion of renewable energy technologies, and can also indirectly affect the export and import performance of countries through R&D activity and market expansion. Thus, it is important to identify not only the domestic diffusion of renewable energy technologies but also foreign trade competitiveness.

1.3 General Research Framework

Figure 1.1 shows a research framework consisting of three empirical studies from the energy paradox to the successful innovation in clean energy technologies, and the role of policies.

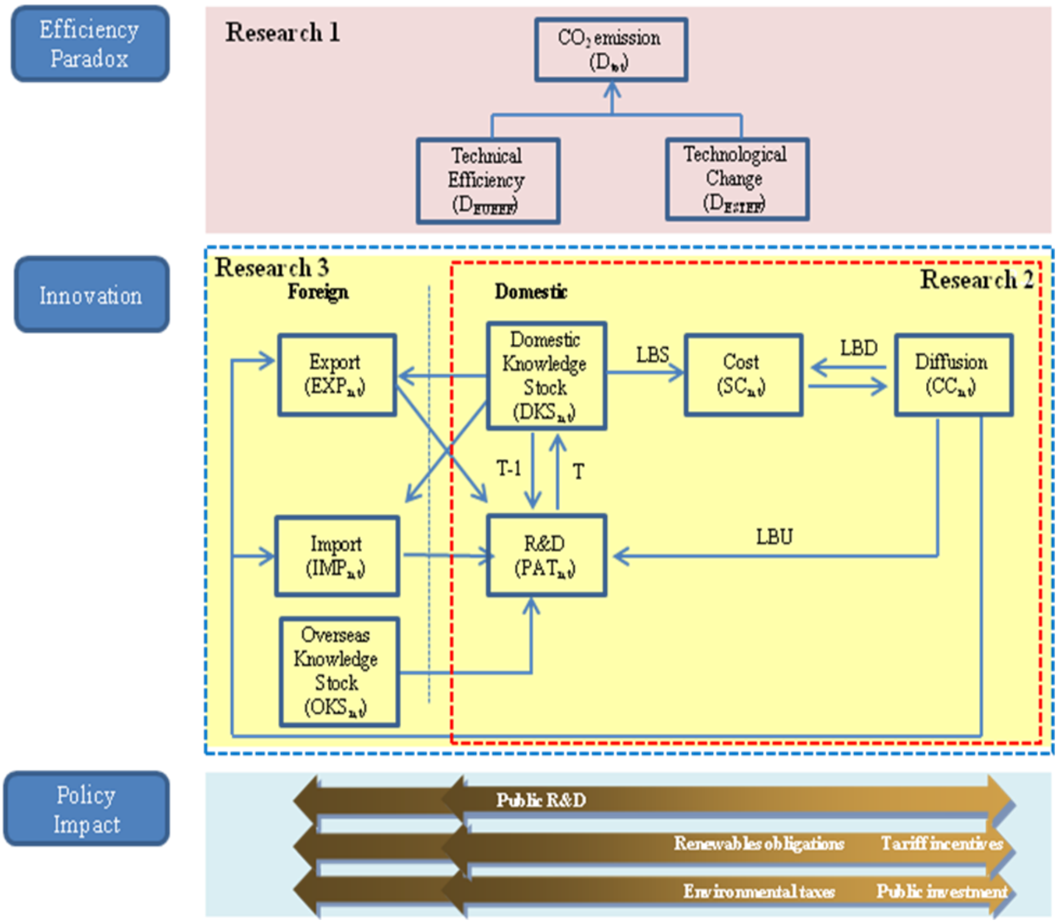

Figure 1.1. Research framework

As the first research issue (Chapter 2), it illustrates how an effective technological diffusion occurs with regard to the reduction of CO_2 emissions, showing temporal evidence of the energy efficiency paradox in energy-use technology. For empirical analysis, energy saving technologies are considered. This study employs the national data of 26 Organisation for Economic Co-operation and Development (OECD) countries and 17 non-OECD countries, from 1990 to 2006, and shows the different economic development stages. In order to accomplish the goal of reducing GHG emissions, a latecomer country has to put in much effort not only to improve its technical efficiency but also to catch up with the advanced technologies, adopting best-practice technologies. The relative performance of energy-saving technologies in a country can be measured using a non-parametric method, that is, data envelopment analysis (DEA). By combining decomposition analysis with DEA, the effect of technological performance on CO_2 emissions can be estimated.

The estimation of the effect of technological performance on CO_2 emissions will provide circumstantial evidence of the energy efficiency paradox in each country, because it identifies the relationship between each country's technical activity using best-practice technologies and the real CO_2 emissions from the industry.

The second research issue (Chapter 3) examines the domestic innovation system and the role of the government policies under the system. This thesis focuses on the renewable energy technologies, that is, solar PV and wind power technologies, which are used to generate electricity. The empirical analysis is conducted using an unbalanced panel dataset covering 16 countries in solar PV and 14 countries in wind power from 1991 to 2008.

While considering endogenous technological changes, it is necessary to notice that each stage not only plays an important role in the technology change process but also interacts with one another in a complex manner. Although the interactions between the three stages are not understood properly due to their complexity, understanding it is regarded as one of the key factors to account for them. The concept of learning is the transfer of knowledge and experience between the actors involved in the technological change process, which is discussed very broadly in theories of technological change. Therefore, this study builds a simultaneous invention, innovation, and diffusion model based on the learning effects through which the interactions between the stages are investigated by an econometric estimation method.

The renewable energy-related policies considered in this study are public R&D, public investment, tariff incentives, renewable energy obligations, and environmental taxes, which comprise the primary energy supply policies (i.e., electric utilities) for renewable energy expansion. Public R&D is defined as the government finances available to support R&D activities from the foundation research level to the commercial development level in private firms as well as in public institutions, which can be a representative technology–push policy. The rest of the policies excluding public R&D focus on reducing costs, increasing demand, and deploying renewable energy technologies (i.e., market-pull policies).

With regard to the technologies in different development stages, for example, solar PV and wind power, the static and dynamic impacts of the renewable energy-related policies on each stage are evaluated on the virtuous cycle formed between the stages, enabling us to compare the policy impacts between the two technologies.

The third research issue (Chapter 4) is primarily an extension of the study on domestic innovation and the role of the policy, but concentrates on the interactions between R&D, technological diffusion, and international trade. It is important to assess not only the domestic diffusion of renewable energy technologies but also the foreign trade competitiveness, considering the renewable energy technologies as sustainable economic growth instruments. This may have significant implications, for example, renewable energy policies for domestic diffusion can affect the exporting and importing performance of countries through R&D activity and market expansion indirectly. Therefore, this study tries to determine the role of renewable energy-related policies in the system.

Chapter 5 provides a summary, along with the findings in the three empirical studies. In addition, the chapter presents the implications to be discussed, the contributions in the empirical approach, and the topic for a future research.

1.4 Contributions

The main contribution of this thesis is the extensive explanations about the seriate social phenomenon from the energy paradox to the diffusion of clean energy technology and the role of the government policies in leading to sustainable industrial growth.

Specifically, using the non-parametric model in Chapter 2, this thesis explains the trends of CO_2 emissions and the energy efficiency paradox by country and region more accurately than statistical estimations. Although there are lively discussions and substantial theoretical bases on the energy efficiency paradox in the literature (Jaffe and Stavins, 1994a; DeCanio and Watkins, 1998; Jaffe et al., 2005; Popp, 2006; Pizer and Popp, 2008), it is difficult to find empirical evidence, because the process from technological change to technological diffusion is not observable. In almost every study, therefore, the energy efficiency paradox has been regarded as a conceptual issue, and most studies attempted to resolve the problem through simulations based on the optimal behavior scenario rather than empirical analysis. However, this thesis provides detailed evidence for the trends of the energy efficiency paradox with market failures through empirical analysis, which can be considered an original quantitative analysis, compared with the previous literatures related to the energy efficiency paradox that depended on qualitative or simulation analysis.

In addition, Zhou and Ang (2008) developed a production-theoretical decomposition analysis (PDA) model and empirically assessed the role of production technologies on

CO_2 emissions for OECD countries for the period 2001–2002. PDA is a significant approach, because it provides detailed information about the influence of production technologies from which more explicit policy implications can be drawn. However, PDA cannot provide the energy mix and industrial structure effects, which have been considered important factors for changing emission levels. As a complement to Zhou and Ang (2008), this thesis can analyze the environmental impacts of energy-use technologies and, at the same time, identify the energy mix and the structure effects. This has great significance, because this thesis provides various underlying factors that affect CO_2 emissions.

Furthermore, a cross-country analysis of emission mitigation potentials reinforces the empirical evidence on a time series, enabling a comparison of the potential to improve market failures by country, and improve reliability.

This thesis has great significance also because it provides an empirical framework to determine the system of endogenous technological-change for a clean energy technology. Unlike many previous studies that determine the interrelations for only a fragmentary part of the system, and not for the whole system (Kouvaritakis et al., 2000; Isoard and Soria, 2001; McDonald and Schrattenholzer, 2001; Miketa and Schrattenholzer, 2004; Klaassen et al., 2005; Junginger et al., 2005; Popp, 2005; Kobos et al., 2006; Sagar and Zwaan, 2006; Söderholm and Klaassen, 2007), this thesis identifies the interaction mechanisms between the invention, innovation, and diffusion stages that comprise the system of technology change for renewable energy.

Furthermore, this thesis expands the empirical framework for the system of domestic technological change to evaluate foreign trade competitiveness, focusing on the interactions between domestic innovations and international trade activity. Since almost no studies have so far integrated domestic innovations and international trade, the models in Chapters 3 and 4 contribute to building a holistic approach to achieve sustainable economic growth as well as domestic innovations and technological diffusion.

The remarkable novelty of this thesis lies in its evaluation of policy impacts, because it establishes a basis to assess the long-term dynamics of policy impacts as well as the static impact of policies. The assessment of the static impacts is significant because it allows policy makers to understand the policy effects at each stage accurately, without any influence from the interactions between the stages. It is also very important to assess the dynamic impacts in policy decisions, because if one does not consider this interrelation between the stages, the policy effects may be underestimated. In addition, this thesis identifies the different policy impacts by technology, thereby providing the foundation to harmonize policies for the symmetric development of technologies.

Thus, this thesis contributes to a better understanding of how the policies interrelate in the endeavor for technological progress. Such an analysis will enable policy makers to understand the aggregated impacts of all the policies over all the stages within the system of technological change and thereby create an efficient long-term strategy for technological progress and sustainable economic growth.

Chapter 2. Energy Efficiency Paradox in Energy-Use Technology[1]

2.1 Introduction

With the worldwide expansion of countries with a burden for mitigation of GHG emissions and the lowering of acceptable GHG levels, emission reduction becomes a key goal in the scheme for future national growth. At the same time, the need to control and mitigate GHG emissions will likely emerge as a worldwide policy agenda. Hence, there will be a need to better understand global GHG emission trends and drivers across countries. Establishing effective GHG mitigation polices requires detailed knowledge regarding past emissions trends, opportunities and potential means for mitigation, and the effectiveness of policies and measures designed to reduce emissions (Kim and Worrell, 2002).

In this chapter, I analyze worldwide carbon dioxide (CO_2) emission trends and the underlying factors creating them. In addition, I concentrate on the impact of technological change in energy-use technology to assess each country's relative effort toward emission mitigation and try to find diffusion characteristics of technology when clean energy technology introduces. I selected 26 Organisation for Economic Co-operation and Development (OECD) countries and 17 non-OECD countries and compared the emission

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[1] This chapter is based on the published paper, Kyunam Kim and Yeonbae Kim, 2012. "International comparison of industrial CO_2 emission trends and the energy efficiency paradox utilizing production-based decomposition", Energy Economics 34, 1724-1741.

trends across them from 1990 to 2006. The selection of countries reflects different economic development status, i.e., I looked at the emission trends in industrialized (OECD) countries and developing (non-OECD) countries.

I also focused on CO_2 emissions from energy use in industry sectors[2]. Because the sectors emit over 30% of global CO_2 emissions (International Energy Agency (IEA), 2009d), the environmental impact of these sectors has become an increasingly important topic of public debate. Furthermore, because environmental regulations in industry sectors directly influence national economic development, each country is concerned about reducing GHG in these sectors. To analyze historical emission changes in industry sectors for each country, I introduce a decomposition analysis that has been widely used as a useful methodology for identifying emission driving factors and quantifying their impacts.

In determining CO_2 emission trends from industry sectors, however, it is necessary to accurately analyze the impact of production technologies including energy-use technology on emissions since they play critical roles on industrial CO_2 emissions. Although CO_2 emissions can be reduced by limiting economic activity and through changing industry structures, these options are impossible to apply, even in developed countries, because they place a great burden on economic growth. Therefore, much attention has been paid to the role of technological improvement in production to mitigate CO_2 emissions at relatively low cost.

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[2] In this study, industry includes manufacturing, services, and agriculture according to the International Standard Industrial Classification of All Economic Activities (ISIC) Rev. 3 (United Nations 1989).

Recently some studies (Pasurka 2006; Wang 2007; Zhou and Ang 2008) have developed methodologies to allow separate assessment of *technical efficiency effects* and *technological change effects* from the effect based on the measure of production technology by combining decomposition analysis with data envelopment analysis (DEA).

The technological change effect refers to emission changes due to the shift of the production frontier over time; it measures the effects of best practice technology. From identifying technological change effects one can analyze how much global technological changes (innovations) contributed to CO_2 emission reductions in the industrial sector. In other words, it indicates how well each country enhances its capability for innovating new, advanced, energy technology. Technical efficiency measures the effect of changes in production efficiency (how far the observed production is from the frontier). It also indicates how efficiently each production unit utilizes relevant technologies and information. From the analysis of these production technology effects, one can empirically trace the seriousness of the energy efficiency paradox at the global level.

The energy efficiency paradox, as major diffusion characteristics of clean energy technology, refers to that situation in which cost-effective energy-efficient technologies are gradually diffused (Jaffe and Stavins 1994a). It can also be expressed as stagnation in the spread of energy efficient technologies and show the result of market failure in clean energy technology. This phenomenon is one of the various results caused by market failure, which occurs by knowledge externality (i.e., public good of knowledge) and low compensation for investment to efficient technology (Jaffe and Stavins 1994a).

Shama (1983) described the basic concept of the energy efficiency paradox and found that for US buildings it exists in the diffusion process of efficient energy conservation technology. Since then, many researchers such as Jaffe and Stavins (1994a), DeCanio and Watkins (1998), and Van Soest and Bulte (2001) established a framework to identify the cause of slow diffusion of cost-effective technologies. In almost all studies, however, the energy efficiency paradox has been regarded as a conceptual issue because it is difficult to assess an actual technological diffusion. Therefore, researchers have attempted to resolve measurement problems through simulations based on optimal behavior scenarios rather than empirical analyses.

By combining decomposition analysis with DEA, I can provide empirical evidence about the relative degree of the energy efficiency paradox in each country even though it is a circumstantial explanation. When considering that energy efficiency paradox emerges from the gap between the existence of most efficient technologies and their adoption by real industry, it is partly explained by identifying the relationship between each country's technical activity with best practice technology (as the potential for adoption of most efficient technology) and real CO_2 emissions from the industry (as a result whether that technology was adopted or not).

Zhou and Ang (2008) provides the theoretical foundation for this analysis developing production-theoretical decomposition analysis (PDA) but they cannot provide the energy mix effect and the industrial structure effect, which have been regarded as important factors to change emissions.

In my approach, I simultaneously estimated both the effect of production technology and the effect of energy mix and industrial structure on industrial CO_2 emissions, which is novel and significant because it can provide more implications for policy makers. Additionally, I account for the energy efficiency paradox by estimating the change of emission reduction potential as well as the change of production technology (change of technical efficiency and technological change) for each country. I calculated the potential for CO_2 intensity improvement (PCII). It measures CO_2 emission efficiency attributed to differences in energy usage technology. By calculating the PCII for each country, I can perform a cross-country analysis and identify the relative degree of adoption of the best energy technology and information available. Therefore, PCII accounts for the relative size of energy efficiency paradox and suggests clues for identifying technologically achievable solutions in the context of each country's existing condition.

The remainder of this chapter is organized as follows. Section 2.2 describes theoretical background based on previous literatures. I account for our empirical model and data in Section 2.3 and Section 2.4, respectively. The results and discussion are presented in Section 2.5. Section 2.6 concludes this study.

2.2 Theoretical Background

2.2.1 Environmental data envelopment analysis

Since Färe et al. (1994b) calculated the relative efficiency change and technical progress of production technology with the Malmquist index using nonparametric programming method, i.e., DEA[3], the DEA framework has been extended into energy and environmental studies. The DEA framework is a nonparametric frontier approach used to measure the productivity in a set of decision making units (DMUs). It constructs the production frontier or most efficient system based on both input and output data of entities and it is calculated as the distance of each entity from the frontier (Färe et al. 1994b). This distance function[4] allows for the comparison of each entity's technical efficiency against the best.

In my approach, I impose an environmental DEA[5] researched by Färe et al. (1996), Zaim (2004), and Zhou et al.(2006, 2007), through which I can consider both desirable outputs and undesirable outputs, i.e., CO_2 emissions. I also identify the technical efficiency and technological changes in each sub-sector of an economy, i.e., agriculture, manufacturing, and service. I conduct the sub-sector analysis so I can show different

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[3] Farrell introduced the basic DEA theory in 1957. After Charnes et al. (1978) started discussions on this topic, Norman and Stoker (1991), Färe et al. (1994a), and Cooper et al. (2006) have developed methodologies as well as applications for DEA.

[4] To assess each entity's productivity, one needs calculate it a distance from the reference technology (i.e., the technology frontier). This distance results from output-oriented or input-oriented distance function. See Färe R, Grosskopf S (2000) for more detailed accounts.

[5] Environmental DEA is a joint production framework. See Zhou et al. (2008) for more detailed explanations and descriptions of applications.

production systems by sub-sector and contribute to measures of industrial structure impacts on CO_2 emissions.

To consider the productivity index associated with a process that jointly produces desirable and undesirable outputs from inputs, it needs to impose several assumptions. First, I assume the freely disposable inputs and the asymmetric treatment of outputs in terms of their disposability: free disposability on desirable outputs and weak disposability on undesirable outputs. Second, I make the null-joint assumption between desirable and undesirable outputs. This means that the producers should always end the production of desirable outputs to eliminate all of the undesirable outputs.

Regarding an explanation about weak disposability of outputs, Färe and Grosskopf (2004) suggest that if there are regulations that restrict undesirable outputs, the reduction target can be achieved by reallocating resources in input to cleanup the undesirable outputs but desirable outputs decline proportionally due to less input into desirable outputs. This implies that the regulation on undesirable outputs leads to the weak disposability of outputs and adjusts the efficiency while sacrificing desirable output consequentially.

For CO_2 emissions, it is appropriate to regard the treatment of outputs as weakly disposal because CO_2 emissions have been affected directly and indirectly by global schemes of climatic change (e.g. United Nations Framework Convention on Climate Change, Intergovernmental Panel on Climate Change and so on) that emerged from the late 1980s as well as by the effort to regulate other undesirable output. In addition, Zaim and Taskin (2000) suggest that even in the absence of regulations, the treatment of undesirable output can be regarded as weak disposability by environmental consciousness of the society. The environmental consciousness is devised as the societies' willingness to plan production reforms that would constrain producers from making undesirable outputs and to bring about the social cost of their actions. Some output sacrifices are unavoidable to meet the required social cost because pollutants are not freely disposable. Therefore, this leads to transforming of the existing production process into the production process that gives up some productive resources to reduce the undesirable outputs.

On the other hands, CO_2 emission mitigation can be accomplished through improvements to several technology parts according to an adoption stage of technology that is in-line with production. Zhou and Ang (2008) considered the production technology as two kinds of clean energy technology, i.e., CO_2 emission abatement technology in output process and energy usage (saving) technology in input process, and identified the technical efficiency and technological change in each technology using input distance functions. Although each technical performance is estimated independently by independent assumption for disposal problem, if the direct link between energy consumption and CO_2 emissions exists in the analysis, estimation results for the performance of CO_2 emission abatement technology might be insignificant.

In this study, it is reasonable to assume a direct link between energy consumption and CO_2 emissions. This is precisely why I used the calculated CO_2 emissions from energy consumption and emission factor of the IPCC guideline because it is difficult to directly measure CO_2 emissions. Assuming that there is no change in CO_2 emission abatement technology, I determined only the technological performance in 'the side of energy usage' by scaling on freely disposable input. Actually, CO_2 emission abatement technology such as representative Carbon Capture and Storage (CCS) technology was almost not introduced into industry in the time period for our analysis (1990-2006).

Therefore, it is appropriate to regard that CO_2 emissions are affected directly by only fuel consumption and fuel mix during this period and to analyze the fuel mix effect on CO_2 emissions instead of analysis for performance of CO_2 emission abatement technology. I point out that even though CO_2 emission reduction technology has not changed, it needs to impose the assumption for weak disposability on CO_2 emissions because the production process has been transformed by various instruments (e.g., regulation, fuel mix technology) excluding this technology.

2.2.2 Decomposition analysis

Decomposition analysis is conducted by using an identity to decompose the changes in CO_2 emissions into several pre-defined factors. Since Hankinson and Rhys (1983) introduced a theoretical foundation to identify components related to the change of energy consumption, decomposition analysis has been developed through various methodological paths in accordance with the theoretical foundations and approximation of factor weights. Among these, decomposition based on index number theory has been intensively used in studies due to its flexibility of adoption as well as a relatively low data requirement (Zhou and Ang 2008). In most relevant studies (Ang and Pandiyan 1997; Ang and Zhang 2000; Lin et al. 2006; Sun 1999; Wang et al. 2005), decomposition analysis has focused on identification of the three major factors affecting emission: emission intensity, energy intensity, and economic activity (or output) effects.

Until a recent date, the previous decomposition analyses from many studies have addressed the impact of the change of production technology (i.e., technical efficiency and technological change) on GHG emissions qualitatively. They explained the production technology impact as a factor leading the change of emission intensity and/or energy intensity (e.g. Greening et al.,1998; Hamilton and Turton, 2002; Kim and Worrell, 2002). These studies did not provide a quantitative analysis for the direct impact of the change of production technology on CO_2 emissions because it is difficult to determine the technological progress and its influence on the environment.

For the last two decades, however, the studies have quantified the efficiency and technical changes of production technology, and efforts to integrate this analytical framework into environmental research have been widely attempted (Färe et al. 1994b; Färe et al. 1996; Pasurka 2006; Wang 2007; Zaim 2004; Zhou et al. 2006, 2007; Zhou and Ang 2008).

Especially, a 2008 study of Zhou and Ang provides the theoretical foundation for this analysis. They developed production-theoretical decomposition analysis (PDA) and also empirically assessed the roles of these production technologies on CO_2 emissions for

OECD countries between 2001 and 2002. They distinguished the category of technology into CO_2 emissions technology and the energy-usage technology. PDA is a significant approach because it provides detailed information about the influence of production technologies from which more explicit policy implications can be drawn. However, this approach has limitations: It does not provide the energy mix effect and the industrial structure effect, which have been regarded as important factors to change emissions.

In next section, I establish the decomposition model with combining environmental DEA to reflect both energy mix and industrial structure effects as well as the production technology effect.

2.3 Empirical Model

2.3.1 Production-based decomposition

I conducted environmental DEA analysis through a Shephard input distance function based on a 2008 study of Zhou and Ang. I consider a production process, which models energy consumption as the inputs[6] and jointly produces value-added as desirable output and CO_2 emissions as undesirable output.

The input distance function for the i industrial sub-sector in k country with time period t can be described as Eq. (2-1) (see Zhou and Ang 2008):

$$D_{Ei}^{t}(x_{i,k}^{t},\, y_{i,k}^{t},\, b_{i,k}^{t}) \;=\; \sup\{\lambda_i : (x_{i,k}^{t} / \lambda_i,\, y_{i,k}^{t},\, b_{i,k}^{t}) \in P^{t}\} \tag{2-1}$$

where $D_{Ei}^{t}(x_{i,k}^{t},\, y_{i,k}^{t},\, b_{i,k}^{t})$ represents the distance from the technology frontier[7] in

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[6] Although multiple types of input such as labor, capital and material can be considered as inputs, only four types of fuels are modeled as input because undesirable output (CO_2 emissions) is dominantly affected by input of energy and, furthermore, we focused on the change in technical efficiency and the technological change in energy use. In the analysis, the inclusion of a single input can make interpretation of the result less complicated as well as simplify the decomposition methodology. On the other hand, an aggregate fuel is used as input in DEA analysis whereas, decomposition analysis used four types of fuels. The reason why we use a different type of fuel data is that it needs to match up DEA model with the decomposition model. In other words, we should impose the aggregate fuel data as input in DEA analysis because the result from DEA indicates technological performance and therefore is related to energy intensity term derived from the aggregate fuel and value-added for each industrial sub sector. Meanwhile, to determine the impact of fuel mix change on CO_2 emissions, it needs to use a disaggregate fuel data in the decomposition model.

[7] In this study, contemporaneous frontier (Shestalova, 2003) was used because this measure was simple for decomposition analysis and could identify the change of production frontier more clearly. The contemporaneous frontier means that it used the data for time T only in order to construct technology frontier for any time T. In other words, this frontier does not depend on data from the previous period.

energy usage side and P^t means a production technology set. The production technology set is referred to as an environmental DEA with the constant return to scale (CRS). This function means that energy consumption $(x_{i,k}^t)$ can be reduced as much as possible with production technology given value-added $(y_{i,k}^t)$, CO$_2$ emission $(b_{i,k}^t)$ and production technology in certain *i* sub-sectors.

To identify the effect of technical efficiency and the technological changes on CO$_2$ emissions, I need to calculate four Shephard input distance functions, i.e., $D_{Ei}^T(x_{i,k}^T, y_{i,k}^T, b_{i,k}^T)$, $D_{Ei}^T(x_{i,k}^{T+1}, y_{i,k}^{T+1}, b_{i,k}^{T+1})$, $D_{Ei}^{T+1}(x_{i,k}^T, y_{i,k}^T, b_{i,k}^T)$, $D_{Ei}^{T+1}(x_{i,k}^{T+1}, y_{i,k}^{T+1}, b_{i,k}^{T+1})$. $D_{Ei}^T(x_{i,k}^T, y_{i,k}^T, b_{i,k}^T) \geq 1$ is a necessary and sufficient condition for $(x_{i,k}^T, y_{i,k}^T, b_{i,k}^T) \in P^T$ and can be interpreted as an inefficiency in production technology. $D_{Ei}^T(x_{i,k}^T, y_{i,k}^T, b_{i,k}^T) = 1$ refers to the most efficient technology. In the case of $D_{Ei}^{T+1}(x_{i,k}^{T+1}, y_{i,k}^{T+1}, b_{i,k}^{T+1})$, it can be interpreted similarly. In a mixed-period distance (i.e., $D_{Ei}^T(x_{i,k}^{T+1}, y_{i,k}^{T+1}, b_{i,k}^{T+1})$, $D_{Ei}^{T+1}(x_{i,k}^T, y_{i,k}^T, b_{i,k}^T)$) , its values means that the input has proportionally minimized contraction so as to make the inputs and outputs in period T+1 (or in period T) feasible in relation to regulated technology in period T (or in period T+1).

To measure the four Shephard input distance functions, I introduce Eq. (2-2), as a single equation (see Zhou and Ang, 2008) because time superscripts are the only difference among the distance functions. In this process, the time superscript is divided into "s" and "t" to define the mixed-period distance. Superscript "s" represents time for the reference set (i.e., a frontier).

$$
\begin{aligned}
[D_{Ei}^{s}(x_{i,k}^{t},\ y_{i,k}^{t},\ b_{i,k}^{t})]^{-1} \ &= \ \min \lambda_i \\
\text{s.t} \quad & \sum_{k=1}^{K} z_k x_{i,k}^{s} \le \lambda_i x_{i,k}^{t}, \\
& \sum_{k=1}^{K} z_k y_{i,k}^{s} \ge y_{i,k}^{t}, \\
& \sum_{k=1}^{K} z_k b_{i,k}^{s} = b_{i,k}^{t}, \\
& z_k \ge 0, \qquad k = 1, 2, \cdots, K \\
& \qquad\qquad s, t \in \{T, T+1\}
\end{aligned}
\tag{2-2}
$$

I established the decomposition model to reflect both the energy mix and the industrial structure effects as well as the production technology effect. When a certain industry sub-sector *i* for country *k* uses fossil fuel energy of *j* type, CO_2 emissions from it in time period *s* can be decomposed with the summation form of the equation of CO_2 emission by each energy type :

$$
b_{i,k}^{s} = \sum_{j} \frac{b_{ij,k}^{s}}{x_{ij,k}^{s}} \times \frac{x_{ij,k}^{s}}{x_{i,k}^{s}} \times \frac{x_{i,k}^{s}}{y_{i,k}^{s}} \times \frac{y_{i,k}^{s}}{y_{k}^{s}} \times y_{k}^{s} \tag{2-3}
$$

where $b^s_{ij,k}$ is the CO$_2$ emissions arising from energy *j* in sub-sector *i*, $x^s_{ij,k}$ is the consumption of energy *j* in sub-sector *i* and $y^s_{i,k}$ is the economic activity level in sub-sector *i*; $b^s_{i,k}$ is the total CO$_2$ emissions in sub-sector *i* where $b^s_{i,k} = \sum_j b^s_{ij,k}$, $b^s_{ij,k} / x^s_{ij,k}$ is the CO$_2$ emission intensity by each energy type, $x^s_{ij,k} / x^s_{i,k}$ is the energy mix variable where $x^s_{i,k} = \sum_j x^s_{ij,k}$, $x^s_{i,k} / y^s_{i,k}$ is the energy intensity, $y^s_{i,k} / y^s_k$ is the economic activity share where $y^s_k = \sum_i y^s_{i,k}$ and y^s_k is the total economic activity level in a country.

Eq. (2-3), which is expressed in the multiplicative form, can be transformed into production-based decomposition model by combining the distance functions. In this process, I can choose one of the two production technologies, i.e. production technology in period T and in period T+1, as reference technology. To avoid the arbitrariness in choice of the reference technology, therefore, I also took the geometric mean of the two production technologies like Zhou and Ang's 2008 study and established a production-based decomposition model like Eq. (2-4) in period T and Eq. (2-5) in period T+1

$$
\begin{aligned}
b^T_{i,k} = \sum_j \frac{b^T_{ij,k}}{x^T_{ij,k}} \times \frac{x^T_{ij,k}}{x^T_{i,k}} \times \frac{x^T_{i,k} / \left[D^T_{Ei}(x^T_{i,k}, y^T_{i,k}, b^T_{i,k}) D^{T+1}_{Ei}(x^T_{i,k}, y^T_{i,k}, b^T_{i,k}) \right]^{1/2}}{y^T_{i,k}} \times \frac{y^T_{i,k}}{y^T_k} \times y^T_k \\
\times D^T_{Ei}(x^T_{i,k}, y^T_{i,k}, b^T_{i,k}) \times \left[\frac{D^{T+1}_{Ei}(x^T_{i,k}, y^T_{i,k}, b^T_{i,k})}{D^T_{Ei}(x^T_{i,k}, y^T_{i,k}, b^T_{i,k})} \right]^{1/2}
\end{aligned}
\tag{2-4}
$$

$$b_{i,k}^{T+1} = \sum_j \frac{b_{ij,k}^{T+1}}{x_{ij,k}^{T+1}} \times \frac{x_{ij,k}^{T+1}}{x_{i,k}^{T+1}} \times \frac{x_{i,k}^{T+1} / \left[D_{Ei}^{T+1}(x_{i,k}^{T+1}, y_{i,k}^{T+1}, b_{i,k}^{T+1}) D_{Ei}^{T}(x_{i,k}^{T+1}, y_{i,k}^{T+1}, b_{i,k}^{T+1}) \right]^{1/2}}{y_{i,k}^{T+1}}$$

$$\times \frac{y_{i,k}^{T+1}}{y_k^{T+1}} \times y_k^{T+1} \times D_{Ei}^{T+1}(x_{i,k}^{T+1}, y_{i,k}^{T+1}, b_{i,k}^{T+1}) \times \left[\frac{D_{Ei}^{T}(x_{i,k}^{T+1}, y_{i,k}^{T+1}, b_{i,k}^{T+1})}{D_{Ei}^{T+1}(x_{i,k}^{T+1}, y_{i,k}^{T+1}, b_{i,k}^{T+1})} \right]^{1/2}$$

(2-5)

The first term on the right side of Eq. (2-4) and Eq. (2-5) accounts for the CO_2 emission factor effect (EMFEF), which is assumed to be constant over time. The second term refers to the energy mix effect (EMXEF). The third term can be interpreted as the potential energy intensity effect (PEIEF) (Zhou and Ang 2008) because it is not the change of real energy intensity but the change of potential energy intensity.

This potential energy intensity is derived from the energy consumption deflated by energy usage performance (Zhou and Ang 2008), which means that the effect of production technology related to energy usage is separated from the real observed-energy intensity. In other words, the potential energy intensity effect adjusts the real observed-energy intensity by its technical inefficiency. Hence, the real observed-energy intensity of a country will be higher than its potential energy intensity due to its technical inefficiency. When a country becomes more technically efficient, its energy intensity declines. I may also interpret this term as the observable energy intensity when inefficiency of the energy-usage technology is improved as much as possible.

The fourth term is the structural effect (STREF) and the fifth term is the economic activity effect (EATEF). The term related to the production technology in energy usage separated from the real observed-energy intensity is also decomposed by two components that are expressed in Malmquist productivity indices: the effect of energy usage efficiency (EUEEF) and the effect of energy saving technical change (ESTEF)[8].

In this study, energy saving technology indicates the technology that can decrease the energy consumption without replacing energy use with labor or capital stock when the same output is produced. For example, the technologies for improving combustion efficiency, for energy reuse and so on can be included. These are the results from DEA analysis and account for the impact of production technology on CO_2 emissions. Hence, I can determine how well each country improves its technical efficiency and enhances its ability to absorb new advanced technology. For example, if both EUEEF and ESTEF are positively associated with reducing CO_2 emissions in a certain country, it means that this country has experienced reducing CO_2 emissions by improving his technical efficiency and adopting the newest technology. This, therefore, empirically shows a degree of energy efficiency paradox.

Using the above notation, the decomposition equation for the aggregate CO_2 emissions in a certain country is as follows:

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[8] Because of the difficulty determining an absolute technological level for each country, we needed to establish a reference point to measure it. Therefore, the technological level of period T is measured as a relative level compared to the level of period T+1 under the same production condition. In the case of T+1, the technological level of period T+1 is measured as a relative level compared to the level of period T under the same production condition. According to Färe et al.(1994b), to prevent an arbitrary benchmark, the shift in energy-saving technology is calculated as the geometric mean of two Malmquist productivity indices from Caves, Christensen and Diewert(CCD, 1982 a,b) type. In this study, the shift of energy saving technology (ESTEF) is expressed as the geometric mean in LMDI formula.

$$b_k^S = \sum_i b_{i,k}^S = \sum_{ij} EMFEF_{ij,k}^S \times EMXEF_{ij,k}^S \times PEIEF_{i,k}^S \times STREF_{i,k}^S \times EATEF_k^S$$
$$\times EUEEF_{i,k}^S \times ESTEF_{i,k}^S$$

$$where \; S \in \{T, T+1\}$$

(2-6)

In our research, I use an index decomposition analysis (IDA) and distance functions because the changes in energy mix and industrial structure as well as the change in production technology should be measured from aggregate CO_2 emissions. To measure the change of these effects, I imposed the logarithmic mean Divisia index method (LMDI), which was recently developed by Ang et al. (1998). The LMDI method, as one of various IDA approaches, has several advantages obtained through the use of a logarithmic mean weight for the approximation. First, the result does not have an unexplained residual term, which makes it more accurate and provides for simplified interpretation. Second, the LMDI is useful for estimating an effect at a sub-group level; the result from the estimation is consistent with the result from an analysis of the aggregate (Ang and Liu 2001). Therefore, for ease in formulation and interpretation, the LMDI method is appropriate to apply to our model.

The change scheme of our model, which is the applied multiplicative LMDI, is described as follows:

$$D_{TOT} = \frac{b_k^T}{b_k^0} = D_{EMFEF} \times D_{EMXEF} \times D_{PEIEF} \times D_{STREF} \times D_{EATEF} \times D_{EUEEF} \times D_{ESTEF} \quad (2\text{-}7)$$

As a result, the impact of each component on CO_2 emissions can be measured as in the following LMDI formulas, Eqs. (2-8) through (2-14):

$$D_{EMFEF} = \exp\left\{\sum_{ij} \frac{(b_{ij}^{T+1} - b_{ij}^{T}) / (\ln b_{ij}^{T+1} - \ln b_{ij}^{T})}{(b^{T+1} - b^{T}) / (\ln b^{T+1} - \ln b^{T})} \ln\left(\frac{EMFEF_{ij,k}^{T+1}}{EMFEF_{ij,k}^{T}}\right)\right\} \quad (2\text{-}8)$$

$$D_{EMXEF} = \exp\left\{\sum_{ij} \frac{(b_{ij}^{T+1} - b_{ij}^{T}) / (\ln b_{ij}^{T+1} - \ln b_{ij}^{T})}{(b^{T+1} - b^{T}) / (\ln b^{T+1} - \ln b^{T})} \ln\left(\frac{EMXEF_{ij,k}^{T+1}}{EMXEF_{ij,k}^{T}}\right)\right\} \quad (2\text{-}9)$$

$$D_{PEIEF} = \exp\left\{\sum_{ij} \frac{(b_{ij}^{T+1} - b_{ij}^{T}) / (\ln b_{ij}^{T+1} - \ln b_{ij}^{T})}{(b^{T+1} - b^{T}) / (\ln b^{T+1} - \ln b^{T})} \ln\left(\frac{PEIEF_{i,k}^{T+1}}{PEIEF_{i,k}^{T}}\right)\right\} \quad (2\text{-}10)$$

$$D_{STREF} = \exp\left\{\sum_{ij} \frac{(b_{ij}^{T+1} - b_{ij}^{T}) / (\ln b_{ij}^{T+1} - \ln b_{ij}^{T})}{(b^{T+1} - b^{T}) / (\ln b^{T+1} - \ln b^{T})} \ln\left(\frac{STREF_{i,k}^{T+1}}{STREF_{i,k}^{T}}\right)\right\} \quad (2\text{-}11)$$

$$D_{EATEF} = \exp\left\{\sum_{ij} \frac{(b_{ij}^{T+1} - b_{ij}^{T}) / (\ln b_{ij}^{T+1} - \ln b_{ij}^{T})}{(b^{T+1} - b^{T}) / (\ln b^{T+1} - \ln b^{T})} \ln\left(\frac{EATEF_{k}^{T+1}}{EATEF_{k}^{T}}\right)\right\} \quad (2\text{-}12)$$

$$D_{EUEEF} = \exp\left\{ \sum_{ij} \frac{(b_{ij}^{T+1} - b_{ij}^{T}) / (\ln b_{ij}^{T+1} - \ln b_{ij}^{T})}{(b^{T+1} - b^{T}) / (\ln b^{T+1} - \ln b^{T})} \ln\left(\frac{EUEEF_{i,k}^{T+1}}{EUEEF_{i,k}^{T}} \right) \right\} \qquad (2\text{-}13)$$

$$D_{ESTEF} = \exp\left\{ \sum_{ij} \frac{(b_{ij}^{T+1} - b_{ij}^{T}) / (\ln b_{ij}^{T+1} - \ln b_{ij}^{T})}{(b^{T+1} - b^{T}) / (\ln b^{T+1} - \ln b^{T})} \ln\left(\frac{ESTEF_{i,k}^{T+1}}{ESTEF_{i,k}^{T}} \right) \right\} \qquad (2\text{-}14)$$

Despite many advantages of LMDI approach, zero and negative value problems are limitations in the calculation. If the data set contains zero values, the LMDI formula may be more complicated due to its logarithmic terms. This study uses more disaggregated data to estimate fuel mix effect and structural effect on CO_2 emissions, and therefore, some zero values for CO_2 emissions occur, depending on the fuel type (i.e., instance of $b_{ij}=0$).

This problem comes from the sub-sector not using certain energy resources, primarily "combustible renewables and waste" as one of four fuel types[9]. In order to resolve this problem, there are several strategies one of which is suggested by Ang and Choi (1997), an approximation method by replacing zero value with a small number and as another solution; Ang et al. (1998) establish analytical limiting values for eight cases. The former is preferable due to its robustness and ease of use while the latter provides a more exact

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[9] According to our IEA (2008a,b) data, for example, Germany had not used combustible renewables and waste source in both service and agriculture sector during the analysis period, 1990-2006. In this case, although Germany's service and agriculture sector cannot produce desirable output (i.e., value-added) through combustible renewables and waste source due to the null-joint assumption between desirable and undesirable outputs, desirable and undesirable output in each sector are still produced by mixing the rest of fuels. In other words, there is no zero values for total energy input, desirable output and total CO_2 emissions in each sub-sector (i.e., $x_i \neq 0$, $y_i \neq 0$ and $b_i \neq 0$), and this means that there is no problem in DEA analysis which does not use fuel specific data.

decomposition result.

In this study, considering the low frequency of zero value occurrences and easiness to implement, I imposed the approximation method in which all zero values in the data were replaced by small positive numbers between 10^{-7} and 10^{-12}. These small positive constants approach zero and, therefore, the result is insignificantly influenced by the approximation. In a recent study, Wood and Lenzen (2006) identified that limiting values are more suitable for a large number of zeros and/or small values, while Ang and Liu (2007a) suggested that in the context of IDA applied to energy, the approximation method is generally robust if the small number is appropriately chosen. On the other hand, Ang and Liu (2007b) provide the solution for negative values as well as zero values by expanding analytical limitations and integrating its procedure for a zero value solution. In this study, some zero values occurred but no negative values occur in a sub-sectoral analysis.

2.3.2 Potential for CO_2 emissions mitigation

I have introduced the method for decomposing each country's aggregate CO_2 emission into the underlying forces within a time series. By focusing on the two components (EUEEF and ESTEF), I can trace the impact of changes in the production technology on CO_2 emissions in each country over time. However, this method does not provide information about the relative abatement level of CO_2 emissions between countries. Therefore, I calculated potential values for CO_2 emission intensity improvement (PCII), which can be used to calculate the relative potential for CO_2 emissions mitigation achieved through adoption of best production technology. PCII is calculated by comparing the potential CO_2 emissions by adopting the best practice technology with the actual CO_2 emissions in each country.

To reflect an achievable potential from only the improved technology, the potential CO_2 emissions are derived with the following assumption and mechanism: if a certain country adopts the best practice energy saving technology available under its existing condition, it can have the improved energy intensity as a lower energy input, and then its CO_2 emissions can also be lower. In this mechanism, to maintain the existing condition, I need to assume that there is no change on CO_2 emission factor, energy mix, industrial structure and economy activity in each country even when best practice technology is adopted. The PCII formula of country k is described as follows:

$$PCII_k = \frac{b_{k,AC} - b_{k,BP}}{y_k} = \frac{\Delta b_{k,POT}}{y_k} \tag{2-15}$$

$$b_{k,BP} = \sum_{ij} \frac{b_{ij,k}}{x_{ij,k}} \times \frac{x_{ij,k}}{x_{i,k}} \times \frac{x_{iBP,k}}{y_{i,k}} \times \frac{y_{i,k}}{y_k} \times y_k \tag{2-16}$$

where $b_{k,AC}$ is the actual(AC) CO_2 emission with the existing technology and $b_{k,BP}$ is the CO_2 emission if the reference or best practice(BP) technology is adopted. $\Delta b_{k,POT}$ is the potential(POT) CO_2 emission mitigation achieved through adopting the best production technology. In the calculation of $b_{k,BP}$, $x_{iBP,k}$ is the energy input under the best practice technology and is calculated by multiplying a weighting factor[10] and actual energy input in *k* country. Based on the assumption above, other terms except for energy intensity should not change, while only energy input ($x_{i,k}$) in energy intensity term should be replaced by an adjusted energy input ($x_{iBP,k}$) due to energy intensity improvement through adopting the best practice energy saving technology. PCII means the additionally improvable CO_2 emission intensity by a country's successful adoption of the best practice technology. And the other side of it is that PCII identifies the stagnation in the spread of energy efficient technologies under a country's existing condition. I, therefore, can account for the relative seriousness of the energy efficiency paradox phenomenon by comparing PCII data across countries.

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[10] The weighting factor is the reciprocal of input distance which was already determined in our DEA because it projects actual energy input into the hypothetical energy input under best practice technology. The reason why we impose input distance function for the weighting factor is that we consider PCII to be affected by input-related technology (i.e., energy saving technology). To measure a gap of 'energy saving technology' between actuality and best practice, it is appropriate to impose input-based distance function in terms of understanding because energy saving technologies makes input change and then, this change of input is reflected in input-based distance. The energy intensity term ($x_{iBP,k}/y_{i,k}$) in Eq. (16) is deeply related to PEIEF in terms of interpretation of their definition: both of $x_{iBP,k}/y_{i,k}$ and PEIEF mean the potential energy intensity which is the energy intensity adjusted by its technical inefficiency. However, energy intensity term in Eq. (16) is calculated by one production technology of certain point in time (T) due to cross-country comparison.

2.4 Data

I applied our proposed model to 26 OECD countries and 17 non-OECD countries from 1990 to 2006 and implemented DEA in every two-year sub-period (i.e., eight two-year pairs from 1990-92 to 2004-06). In other word, the data in this study are constructed by bi-annual (i.e., 1990, 1992, . . . , 2004, 2006). I judged that it was general but reasonable to determine the trace of bi-annual given the long term for analysis and the non-rapid change in energy saving technology. More accurate results can be obtained with the DEA by increasing the DMUs (i.e., countries) for DEA analysis. I tried to collect data for as many countries as possible from each region by keeping the data consistent in quality across countries and many major countries could be the targets for DEA analysis. The selection of countries reflects various economic development statuses, i.e., I looked at the emission trends in the industrialized (OECD) countries and the developing (non-OECD) countries. The selected countries also represent each region, i.e., EU, Asia, North America, Oceania, Latin America and Africa. In addition, the production frontier reflects the latest change of technology because it includes most regional EU countries (i.e., Northern EU, Southern EU, Western EU, Eastern EU) where regulations and the newest technologies related to environment are actively introduced. I, therefore, believe that our result is reliable and it can suggest new implications.

In this study, the economic activities for each country were categorized into three industries (i.e., manufacturing, service and agriculture). As a cross-national analysis, I focused on identifying general trends and factors affecting CO_2 emissions from the three representative industries of each country. There may be variations in carbon intensities among sub industries within each sector when aggregated data was used. Despite of this variation, I used aggregated data in order to minimize the variation in industrial structure among nations and include more DMUs in our DEA analysis. Data requirements also restrict the level of sector disaggregation. Additionally, in the case of OECD countries, in sub industry, carbon intensities vary but the shares of value-added have not changed greatly during our analysis period[11]. This can be a foundation for aggregating sub industries because it implies that the change of energy intensity for aggregate manufacturing sector represents the average trend of energy intensity in sub industries.

Based on ISIC Rev. 3 (United Nations 1989), I grouped the various economic activities linked to overall industry into sub-sector categories and readjusted the classifications of each database to make them suitable for our analysis. Table 2.1 shows that the economic activities in the database for both input and output are geared toward our industrial classification.

The data used for both the environmental DEA and the decomposition analysis involve energy consumption (in million tonnages of oil equivalent, Mtoe), real gross value added (in billion US$, 1990) and energy-related CO_2 emissions (in million tonnes, Mt) for each industrial sub-sector.

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[11] We determined not only the share change of total value-added but the average of share change of each country in 26 OECD countries by using OECD STAN Database during our analysis period. These are available upon a request.

Table 2.1. Industry classification based on ISIC Rev.3

Sub-sector	ISIC (Rev.3) Section	Gross Value-Added Data Base[a]	Energy Balance Data Base of OECD and non-OECD[b]
Agriculture	A	Agriculture, hunting, and forestry	Agriculture/forestry
	B	Fishing	Fishing
Manufacturing	D	Manufacturing	Industry sector
Service	G	Wholesale and retail trade	Commerce and public services
	H	Hotels and restaurants	
	J	Financial intermediation	
	K	Real estate, renting, and business activities	
	L	Public administration and defense	
	M	Education	
	N	Health and social work	
	O	Other community, social, and personal service activities	
	P	Private households with employed persons	

[a] United Nations Statistics Division (2009).

[b] International Energy Agency (2008a, 2008b)

The data used for both the environmental DEA and the decomposition analysis involve energy consumption (in million tonnages of oil equivalent, Mtoe), real gross value added (in billion US$, 1990) and energy-related CO_2 emissions (in million tonnes, Mt) for each industrial sub-sector. In energy consumption as input, I collected data from four fuel types, i.e., coal and coal products, petroleum products, natural gas, and combustible renewables and waste, which form most of the energy consumption for industry[12]. The energy data sources are the Energy Balances of OECD Countries and the Energy Balances of Non-OECD countries published by the IEA (2008a,b). For value added as desirable output, I referred to the National Accounts Estimates of Main Aggregates Database, 2009, which is available online through the United Nations Statistics Division (2009). I extracted the real gross value added by kind of economic activity as expressed in international constant price (1990 US$). I also calculated CO_2 emissions as undesirable outputs by applying the CO_2 emission factor, which varies with the fuel type according to the Revised 1996 IPCC Guidelines (Intergovernmental Panel on Climate Change 1997). The emission factor, i.e., the average emission factors per fuel type, used in this study are presented in Table 2.2.

Meanwhile, this study solved the four distance functions by DEA Excel Solver developed by Zhu (2003), and decomposes the underlying factors by Excel program.

Table 2.2. CO_2 emission factor for a type of fuel (in Mt / Mtoe)

Type of Fuel	CO_2 Emission Factor
Coal and coal products	4.10
Petroleum products	3.07
Natural gas	2.35
Combustible renewables and waste	3.64

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[12] This study considers the only primary resources that enable direct measurement of CO_2 emissions in each industrial sub-sector. Electricity as a secondary energy resource is not reflected in our analysis.

2.5 Result and Discussion

In the result, it is worth noticing that several countries experience infeasible linear programming problem that emerges in the calculation of mixed-period distance. This problem is attributed to the assumption of weak disposability on undesirable outputs when distance of observations in period T+1 is determined by the production frontier established by observations in period T (Pasurka, 2006).

In our empirical analysis, when imposing the reference technology in 1990 and the observations in 2006, infeasible LP problems for each of the three industrial sub-sectors were encountered as follows: manufacturing sector - Switzerland; service sector - Brazil, Denmark and Sweden; agriculture sector - Switzerland, Bolivia, Ecuador and Pakistan. The frequencies of these problems - this is calculated as the ratio of infeasible LP problems to total samples - are as low as 0.02 (manufacturing), 0.07 (service) and 0.09 (agriculture). Asmild et al. (2004) and Färe et al. (2007) suggested that when there are too many occurrences of infeasible LP problems, "windows" approach[13] for establishing production frontier may reduce this problem. However, I continued to use our contemporaneous frontier approach because of low frequency of infeasible LP problems.

In addition, if windows frontier is imposed, I may not be able to clearly determine the change of technology according to time flow because windows frontier may depend on the previous period. Therefore, it is appropriate to use contemporaneous frontier because

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[13] "Windows" means that the production technology in any period T consists of observations from present and previous periods (i.e., T, T-1 and T-2). See Pasurka (2006) and Färe et al. (2007) for more detail.

this study focuses on determining the change in technical efficiency and the change of technology.

Table 2.3. The change of CO_2 emissions and the effects of contributing factors in OECD countries, 1990-2006

Country	D_{TOT}	D_{EMXEF}	D_{PEIEF}	D_{STREF}	D_{EATEF}	D_{EUEEF}	D_{ESTEF}
Australia	1.2850	0.9661	0.9980	0.7814	1.6512	1.0321	1.0008
Austria	1.3879	0.9836	0.9376	1.0366	1.4326	1.0055	1.0078
Belgium	1.0454	0.9278	0.8415	0.9305	1.3505	1.0506	1.0141
Canada	1.2911	1.0188	0.8739	0.9459	1.5688	0.9591	1.0190
Czech	0.4262	0.8733	0.2981	1.0662	1.5169	1.0591	1.0127
Denmark	0.8956	0.9641	-	0.9966	1.3625	0.9951	-
France	0.9363	0.9750	0.7239	1.0018	1.3499	0.9653	1.0161
Germany	0.6141	0.8705	0.5435	0.9331	1.3346	1.0188	1.0229
Greece	1.0206	0.9309	0.8040	0.9080	1.4129	1.0643	0.9986
Hungary	0.6312	0.9860	0.4257	1.0711	1.4385	0.9595	1.0171
Ireland	1.2832	0.9646	0.6331	0.8518	2.4886	0.9736	1.0182
Italy	1.0684	0.9778	0.9667	0.9277	1.1919	1.0175	1.0046
Japan	0.9996	0.9742	0.8290	0.9496	1.2971	0.9871	1.0179
Korea	1.3145	1.0032	0.5403	1.1206	2.2065	0.9638	1.0177
Mexico	0.8720	0.9828	0.5639	1.0207	1.5542	0.9885	1.0034
Netherlands	0.9353	0.9899	0.7015	0.9320	1.4776	0.9604	1.0184
New Zealand	1.0901	0.9866	0.7735	0.9380	1.5303	0.9905	1.0047
Norway	1.0654	0.9707	0.8084	0.8353	1.6210	1.0049	0.9979
Poland	0.9738	0.9228	0.3178	1.1002	2.9497	1.0073	1.0157
Portugal	1.0694	0.9258	0.8928	0.9235	1.2902	1.0857	1.0002
Slovakia	0.3991	0.8613	0.2195	1.2071	1.6258	1.0517	1.0226
Spain	1.3354	0.8938	0.9469	0.9351	1.4944	1.1297	0.9996

Sweden	0.8686	0.9902	-	1.2378	1.5913	0.9171	-
Switzerland	1.0297	0.9624	-	1.0233	1.1955	0.9775	-
United Kingdom	0.7773	0.9081	0.6906	0.8177	1.4511	1.0296	1.0146
United States	0.8970	0.9687	0.5888	0.9877	1.6181	0.9672	1.0173
Geometric mean[a]	0.9402	0.9521	0.6471	0.9742	1.5405	1.0052	1.0114

[a] Denmark, Sweden and Switzerland in infeasible LP problems are excluded in the calculation of geometric mean.

Table 2.4. The change of CO_2 emissions and the effect of contributing factors in non-OECD countries, 1990-2006

Country	D_{TOT}	D_{EMXEF}	D_{PEIEF}	D_{STREF}	D_{EATEF}	D_{EUEEF}	D_{ESTEF}
Argentina	1.4117	0.9858	0.8398	1.0153	1.6923	0.9844	1.0082
Bolivia	2.8678	1.0417	-	1.0199	1.6843	0.9633	-
Brazil	1.6938	0.9817	-	0.9473	1.5074	1.0263	-
Chile	2.0159	0.9300	1.0385	0.9067	2.1179	1.0748	1.0112
China	1.6855	0.9771	0.3024	1.4079	3.9648	1.0092	1.0127
Cuba	0.3602	0.8026	0.4310	0.6912	1.3414	1.1013	1.0196
Ecuador	0.9525	0.9721	-	0.7214	1.3998	1.0126	-
Guatemala	2.2382	1.0762	1.3787	0.9049	1.6681	0.9950	1.0044
India	1.3927	0.9657	0.5012	1.1036	2.5053	1.0222	1.0181
Indonesia	2.1557	1.1456	0.8863	1.1938	1.8959	0.9333	1.0050
Pakistan	2.0549	0.9618	-	1.1758	2.1798	1.0286	-
Peru	1.4472	1.0154	0.7724	1.0426	1.8000	0.9800	1.0032
Philippines	1.4358	1.0511	0.8604	0.9854	1.6506	0.9655	1.0109
South Africa	0.9034	0.9684	0.6655	0.9086	1.4950	1.0186	1.0131
Tanzania	1.7568	1.0049	0.7986	1.0302	2.1318	0.9785	1.0188
Uruguay	0.9472	0.9595	0.7727	0.9762	1.2838	1.0165	1.0029
Zimbabwe	0.5537	0.9653	0.8304	0.8750	0.7714	1.0063	1.0171
Geometric mean[a]	1.3620	0.9860	0.7268	0.9808	1.7285	1.0061	1.0112

[a] Bolivia, Brazil, Ecuador and Pakistan in infeasible LP problems are excluded in the calculation of geometric mean.

2.5.1 Decomposition result

Tables 2.3 and 2.4 present the decomposition results of the change of industrial CO_2 emissions for OECD and non-OECD countries from 1990 to 2006 respectively. Also Appendix 1 shows the result by time division to provide accurate assessment about technology performance by time. The tables show not only the changes of total emissions (D_{TOT}) but the six contributors that affect CO_2 emissions (i.e., D_{EMXEF}, D_{PEIEF}, D_{STREF}, D_{EATEF}, D_{EUEEF} and D_{ESTEF}). Numerical values greater than one can be interpreted as showing increased CO_2 emissions, while values less than one suggest that the factor contributes to a decrease in CO_2 emissions. Values equal to one indicate that there is no change of factor contributing to CO_2 emissions.

From D_{TOT} in Table 2.3 and Table 2.4, one can see that despite national variations, aggregate CO_2 emissions for OECD countries decrease while those for non-OECD countries increase in general. Fig. 2.1 shows the trend of the changes of industrial CO_2 emissions in the two groups, i.e., OECD and non-OECD countries. The CO_2 emissions from OECD countries have decreased approximately 7%, from 2600 Mt in 1990 to 2421 Mt in 2006. Many of the countries that experienced decreased CO_2 emissions belong to regions with a relatively high emission-intensity, i.e., western Europe, Asia (Korea and Japan) and North America, which may influence the overall emission declines seen in these regions. One can also see that emissions from eastern European countries with economies in transition have largely dropped. According to the IEA (2009d), the sharp drops are caused by a rapid decline in industrial production as a consequence of the 1989 collapse of their centrally planned economies. Meanwhile, from 1990 through 2005, the increase in non-OECD countries (approximately 59% from 1621 to 2580 Mt during the same period) outweigh the decline in emissions for OECD nations. In the non-OECD group, Asia accounts for more than 80% of CO_2 emissions, which indicates that Asian countries, including China and India, with large scale of economies play a dominant part in increasing CO_2 emissions among non-OECD nations.

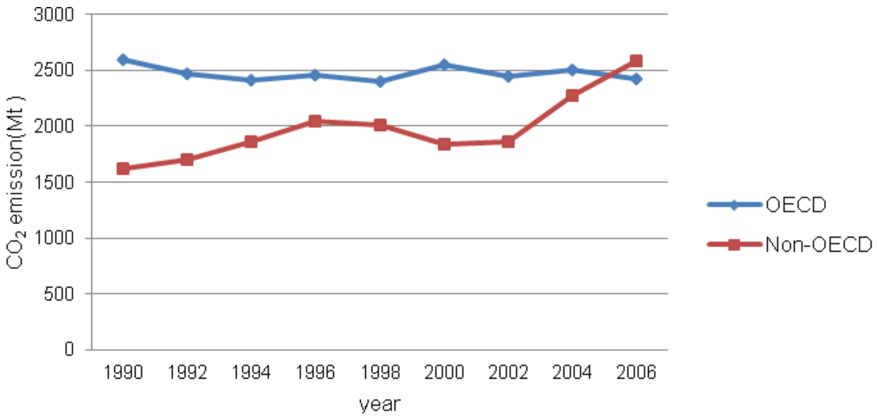

Figure 2.1. Changes in CO_2 emissions for OECD and non-OECD countries, 1990-2006

The energy mix change (D_{EMXEF}) has led to a reduction of CO_2 emissions in almost all OECD and non-OECD countries that switched to fuels with lower carbon content. In the OECD group, however, the energy mix change for Canada and Korea contributes to their increase in CO_2 emissions[14]. Brazil, China, and India, the new economic powerhouse, have shown a surprising decline in CO_2 emissions, despite rapid industrialization, by improving the energy mix. For example, the decline of CO_2 emissions in Brazil comes from increased using of natural gas which has relatively low carbon contents. The proportion of coal and coal products and petroleum products has declined respectively 0.8% and 6.8% while the proportion of natural gas has increased 7.7% from 1990 to 2006. The effects of energy mix changes are among the most significant contributors to decreased emissions.

As mentioned in Section 2.3, potential energy intensity (D_{PEIEF}) is regarded as a hypothetical figure because it is calculated by excluding the effects of efficiency and technical change in terms of production technology. D_{PEIEF}, therefore, measures the impact of energy intensity change on CO_2 emissions without inefficiency of the energy-usage technology.

In our result, the values of D_{PEIEF} are almost less than unity and, this means that the

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[14] In Canada, the proportion of natural gas with the lowest carbon contents in the whole economy had decreased from 54.7% to 50.0% during 1990-2006. At the same time, the proportion of both petroleum products and combustible renewable and waste which have higher carbon contents than natural gas had increased respectively from 27.4% to 30.6% and from 12.1% to 14.2% in the same period. And the proportion of coal and coal products had changed relatively little– only 0.6% drop. Therefore, we can find that Canada switched to fuels with higher carbon contents, which led to increase in its CO_2 emissions. On the other hand, in case of Korea, it is not easy to identify the cause concerning the impact of fuel mix change on CO_2 emissions from the whole economy proportion change of fuels because proportion of fuels except for petroleum products had all increased; natural gas: 22.8% increase, coal and coal products: 11.2% increase, combustible renewable and waste: 4.7% increase and petroleum products: 39% decrease. Therefore, unlike the case of Canada, there is a limit to fragmentarily identifying the cause from only proportional change of fuels in the whole economy and thus we need to consider the relative scale for consumption, the intrinsic carbon contents and logarithmic mean weight by sub-industry overall. Considering these factors, fuel mix change by Eq. (9) is estimated to influence CO_2 emissions increase consequentially. This study, therefore, suggests that the cause concerning the impact of fuel mix change on CO_2 emissions in these countries needs to be more carefully analyzed.

change of energy intensity will contribute a reduction on CO_2 emissions when inefficiency of the energy-usage technology is improved as much as possible. These decreases are caused by varied national factors, such as best practice in energy usage technology, high labor productivity, energy demand change and improvement for energy infrastructure. Also, according to the IEA (2009d), CO_2 emissions from industry have been falling all over the world and the IEA attributed the cause to energy decoupling from economic growth. In other words, the creation of value added requires less energy than in the past and the economic growth is derived from less energy-intensive industries.

Therefore, energy consumption has declined over time, which has led to a reduction in energy intensity. In particular, eastern European countries have experienced a large impact due to D_{PEIEF}, perhaps because of the structural changes of their economies or policies. On the contrary, some Latin American nations (Bolivia, Brazil, Chile, and Guatemala) have experienced increased potential energy intensity that leads to increasing CO_2 emissions.

The impact of industrial structure change on CO_2 emissions (D_{STREF}) is worth study. For identifying this impact, I determined the proportional change of three industrial sectors by using their value-added. In the OECD group, shown in Fig. 2.2, while the share of value-added in manufacturing sector has slightly decreased, it has slightly increased in the service sector. This change may influence decreasing CO_2 emissions for many OECD countries. However, in several countries including Czech, Korea, Mexico, Slovakia, Sweden and so on, the industrial structure has changed such that CO_2 emissions have increased.

In the non-OECD group, the manufacturing sector has seen an 14% increase in its share of value-added, from 30% in 1990 to 44% in 2006, while it declined 7% in the service sector during the same period (from 48% in 1990 to 41% in 2006). As a result, for a few non-OECD countries, the structural shift has affected CO_2 emissions. China experienced the greatest change of industrial structure, which led toward a positive impact on CO_2 emissions (1.4079), reflecting the rapid industrial reorganization and development plans after market reform.

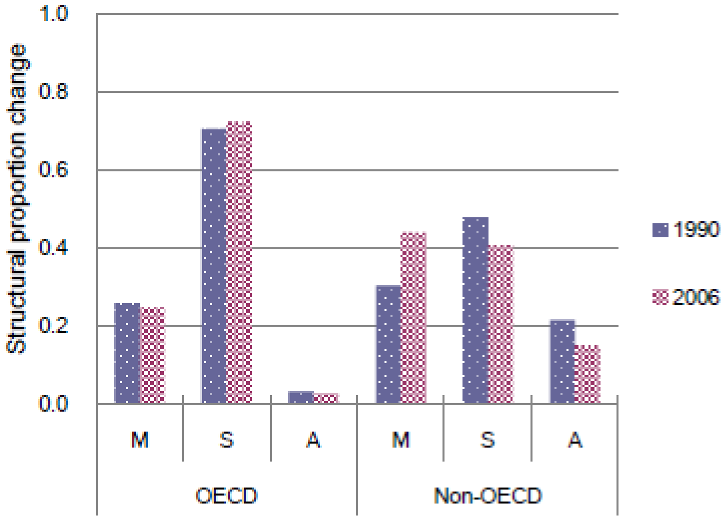


Figure 2.2. The structural changes in industry (M: Manufacturing, S: Service, A: Agriculture, hunting, forestry and fishing) for OECD and non-OECD countries from 1990 to 2006

Economic activity change (D_{EATEF}) can be considered a dominant contributor of CO_2 emissions. In all countries except Zimbabwe, it has played the most dominant role in increasing CO_2 emissions, and the change for non-OECD group (1.7285) is greater than for the OECD group (1.5405). Brisk economic growth of developing countries with large economies, such as Brazil, China, and India, contribute to the increased values. China, in particular, experienced a substantial change in economic activity to increase emissions (3.9648) in its CO_2 emission change. In the case of OECD countries, Ireland, Korea, and many countries in eastern Europe have experienced increasing CO_2 emissions by economic activity expansion. In Zimbabwe, however, unlike other countries (even those in Africa), economic activity contributes to decreased CO_2 emissions.

On the other hand, the energy usage efficiency effect (D_{EUEEF}) and energy-saving technology effect (D_{ESTEF}) are two factors of production technology that are separated from energy intensity, and their components are based on a comparison, through the DEA framework, of all countries on the best-practice production frontier. Therefore, the impact of these contributors depends on a relative difference of production technology, which varies by country. So, I determined a property in each regional group rather than each country.

Table 2.5 shows the change of D_{EUEEF} and D_{ESTEF}, respectively, in every region during the period 1990-2006. The numerical value in each region was calculated by geometric mean of components for countries within the region. It shows mixed results but generally reveals that technical change has a weaker influence on the reduction of CO_2 emissions than other underlying factors.

Some countries in western and northern Europe, Asia, and North America have improved their energy usage efficiency compared with others and this has contributed to decreased CO_2 emissions. Meanwhile the component of D_{EUEEF} in eastern and southern Europe, Oceania, Africa, and Latin America slightly affects growing CO_2 emissions.

Table 2.5. Change of energy usage efficiency and energy saving technology in every region, 1990-2006

	OECD							Non-OECD		
Region	Western Europe	Eastern Europe	Southern Europe	Northern Europe	Oceania	Asia[a]	North America	Asia[b]	Africa	Latin America
D_{EUEEF}^{c}	0.9972	1.0186	1.0735	0.9716	1.0111	0.9754	0.9715	0.9911	1.0010	1.0163
D_{ESTLEF}^{c}	1.0160	1.0170	1.0007	0.9979	1.0027	1.0178	1.0132	1.0117	1.0163	1.0082

[a] Japan and Korea in OECD are only included

[b] Several developing non-OECD nations are included. (China, India, Indonesia, Pakistan, Philippines)

[c] Seven countries in infeasible LP problems are excluded in the calculations.

The change of energy saving technology (D_{ESTEF}) is another factor of the effect of production technology. It reflects how well each country enhances its capability for innovating new, advanced energy technology. From Table 2.5, one can see that these components excluding northern Europe play a positive role to increase CO_2 emissions and therefore can suggest that global innovations related to energy saving technology have not been significant in reducing CO_2 emissions in our analysis period.

Furthermore, as shown in from Figs. 2.3 through 2.12, the change in technical efficiency and technological change for countries within each region is easier to see with more detailed information acquired over time. On one hand, in northern and western Europe, OECD nations of Asia, and North America, the changes in energy usage efficiency generally contribute to gradual decreased CO_2 emissions. On the other hand, for many OECD regions, the changes in energy-saving technology increased CO_2 emissions until the mid-1990s, but its impacts were lower after the early 2000s. This result indicates that OECD countries have recently tried to enhance their capability for inventing new energy-saving technologies or absorbing external technologies to mitigate their CO_2 emissions.

Meanwhile, many countries in southern and eastern Europe, Oceania, and non-OECD regions have less significant contribution of technical efficiency on reduction of CO_2 emissions relative to that of other regions. The changes of energy-saving technology, especially, in eastern Europe and non-OECD countries do not contribute to reduce CO_2 emissions and, furthermore, these impacts are not improved over time. As a result, many countries in eastern Europe and non-OECD nations have not caught up with the leaders in energy usage efficiency and until recently had not innovated activities for new energy technology creation.

It is worth considering the issue about energy efficiency paradox in line with our result. Energy efficiency paradox refers to whether the potential for reducing CO_2

emissions with more efficient technology induces decreased CO_2 emissions. If a country with the potential to catch-up with the best practice practically experiences decrease in CO_2 emissions (i.e., when DEUEEF < 1), then the relative degree of energy efficiency paradox may be less than it was in the past by improving his technical efficiency. And, if a country with potential to establish technical progress practically experiences decrease in CO_2 emissions (i.e., when DESTEF < 1), then the relative degree of energy efficiency paradox may be less than it was in the past by enhancing his capability for innovating new, advanced, energy technology.

As shown in Appendix 1, both OECD and non-OECD experience energy efficiency paradox that global innovations related to energy saving technology have not been diffused well in 1990s. Despite national variation, this results from that in this period, fossil fuel consumption in each county has been growing by global economic boom but there are little international regulations or consensus to reduce GHG emissions.

Entering to 2000s, OECD countries that are levied GHG reduction by introducing Kyoto protocol begin to improve energy usage efficiency and to introduce best-practice technology for energy-saving. In addition, the growing energy price promotes the countries to innovate their production technology. As a result, in the period of 1998-2006, the relative degree of energy efficiency paradox in OECD appears to be less than the period of 1990-1998.

However, most of non-OECD countries have still experienced energy efficiency paradox in the period of 1998-2006 because they have not invested the advanced technology although they have rapid economic growth.

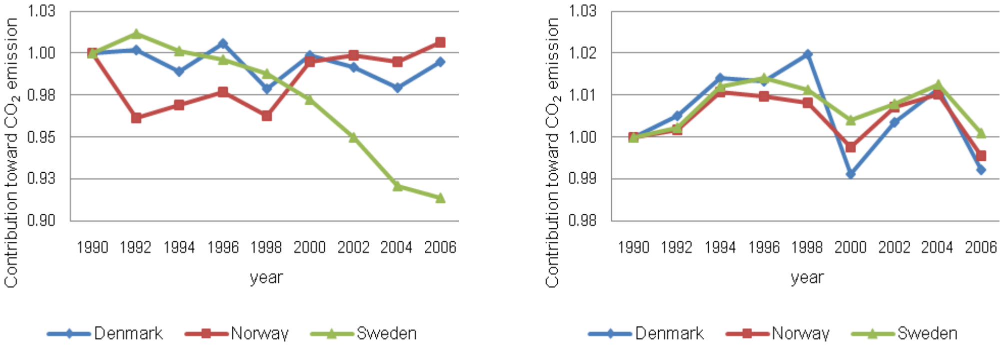
These results are supported by several reports and previous literatures. The energy efficiency paradox can be less by increase in demand of clean energy technology. According to IEA (2008e), OECD countries have reduced their primary oil demand starting from 2000, improving their energy intensity and introducing energy efficiency and saving technology. However, the oil demand for non-OECD has continuously grown.

Meanwhile, a national policy for energy efficiency that is changed by rising energy price and international regulations is dominant in improvement of energy efficiency paradox. Since 2000, EU confronted by global warming and rising energy prices has established a strong energy policy including reinforcement of energy security, changes in market structure, diversification in energy sources and energy efficiency improvements (IEA, 2008f). Especially, EU-ETS (Emission Trading System) provides firms with incentives to reduce GHG emissions, and furthermore the opportunity to diffuse the advanced energy saving technology (IEA, 2008f).

Since 2001, the United States has considered energy efficiency improvement as an important part by the National Energy Policy (NEP), and federal government has been imposing information deployment, standard establishment and R&D encouragement (IEA, 2008g). The Energy Policy Act of 2005 enacted in 2005 is the one of most effective instruments to affect energy efficiency improvements and the use of clean energy technologies since 1992. This policy has greatly contributed to diffuse the best practice technology providing new statutory standard, the strengthening of federal activities and the motivation for voluntary improvements (IEA, 2008g).

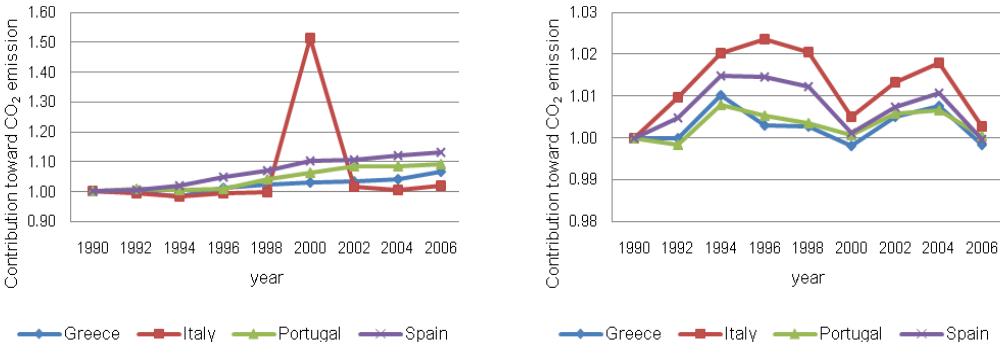
China as representative country in non-OECD has reduced R&D investment for energy efficiency improvement from 13% in 1980 to 4% in 2003 despite its rapid economic growth. This results in growing energy efficiency paradox in China (Lin, 2005).

From these results, I can see that the energy efficiency paradox phenomenon is less prevalent in northern and western Europe, OECD countries in Asia, and North America than in other regions. On the other hand, this study limits the production technology to only the energy-usage technology with only fuel use as an input. I recognize that our analysis is only targeting the efficiency paradox in the side of our energy-usage although there are various energy technologies according to the energy source, energy life cycle and so on.



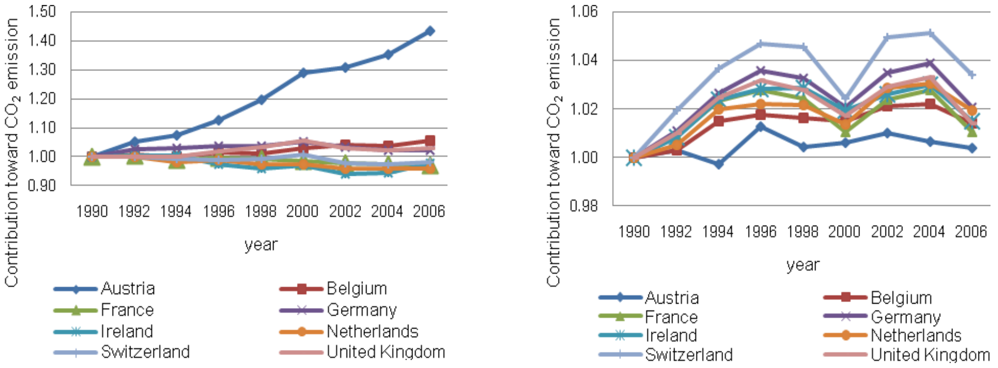
(a) (b)

Figure 2.3. a) Energy usage efficiency effect and b) Energy saving technological change effect within northern Europe



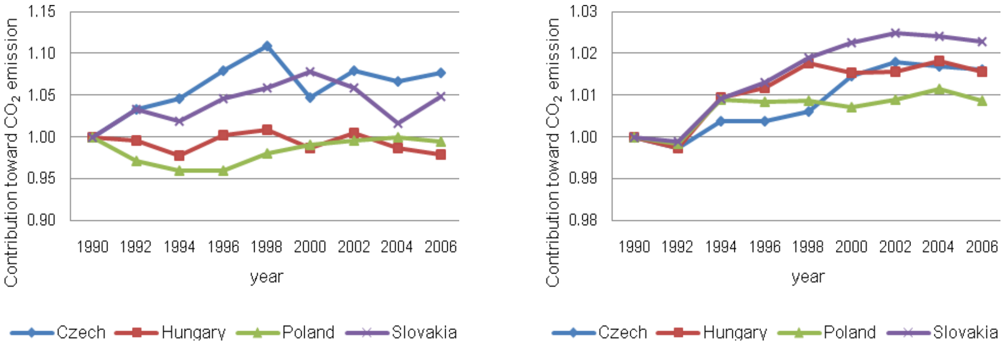
(a) (b)

Figure 2.4. a) Energy usage efficiency effect and b) Energy saving technological change effect within southern Europe



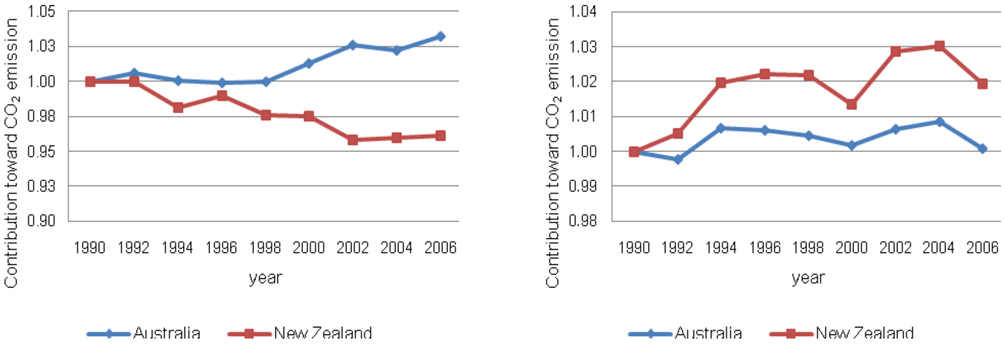
(a) (b)

Figure 2.5. a) Energy usage efficiency effect and b) Energy saving technological change effect within western Europe



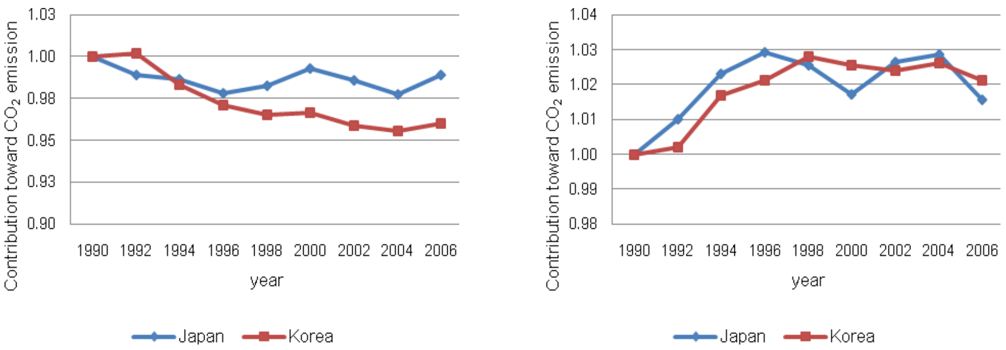
(a) (b)

Figure 2.6. a) Energy usage efficiency effect and b) Energy saving technological change effect within eastern Europe



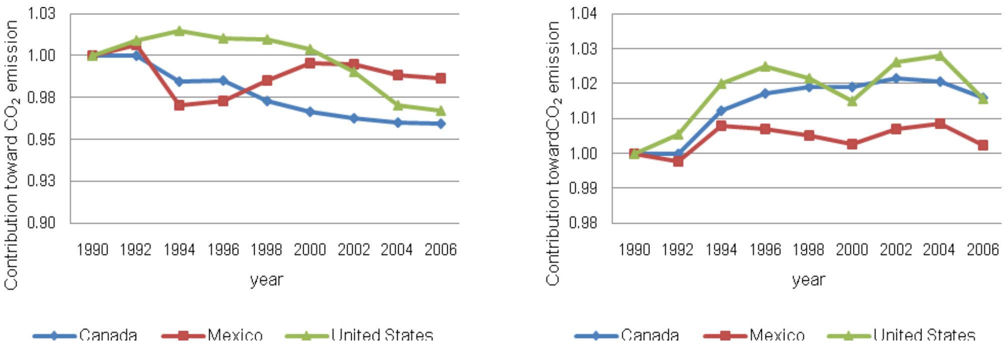
(a) (b)

Figure 2.7. a) Energy usage efficiency effect and b) Energy saving technological change effect within Oceania



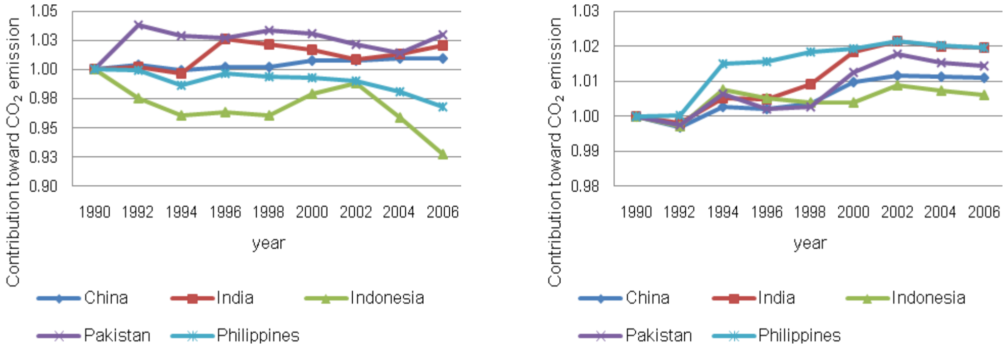
(a) (b)

Figure 2.8. a) Energy usage efficiency effect and b) Energy saving technological change effect for OECD countries within Asia



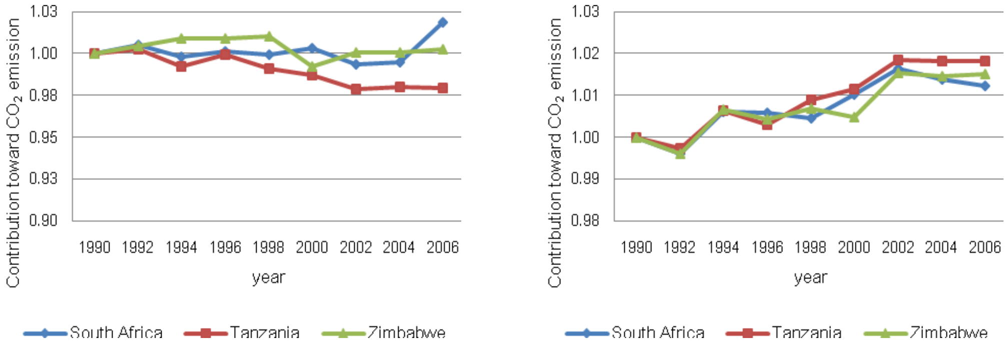
(a) (b)

Figure 2.9. a) Energy usage efficiency effect and b) Energy saving technological change effect within North America



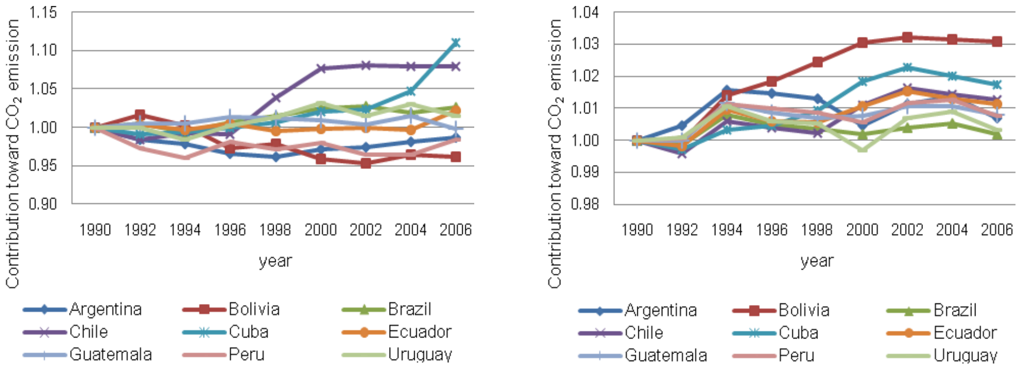
(a) (b)

Figure 2.10. a) Energy usage efficiency effect and b) Energy saving technological change effect for non-OECD countries within Asia



(a) (b)

Figure 2.11. a) Energy usage efficiency effect and b) Energy saving technological change effect within Africa



(a) (b)

Figure 2.12. a) Energy usage efficiency effect and b) Energy saving technological change effect within Latin America

2.5.2 International comparison of the potential for emission mitigation

To compare potential for CO_2 emission mitigation, I calculated the potential values for PCII for each country (Table 2.6). The smaller the numerical value of PCII is, the closer the technological gap between each country’s actual technology and the best practice technology is. PCII data indicate the successfulness of a country’s adoption of advanced and effective technology and thus its ability (or capability) to ameliorate the energy efficiency paradox. Therefore, by comparing PCII data across countries, I can also account for the relative degree of energy efficiency paradox.

Table 2.6. Relative potential for CO_2 intensity improvement for all countries (Mt/ billion US$)

	1990	1992	1994	1996	1998	2000	2002	2004	2006
Australia	0.044	0.043	0.042	0.041	0.039	0.040	0.036	0.036	0.038
Austria	0.021	0.021	0.020	0.024	0.022	0.022	0.024	0.023	0.022
Belgium	0.041	0.042	0.042	0.047	0.046	0.046	0.042	0.040	0.040
Canada	0.088	0.088	0.083	0.085	0.074	0.072	0.069	0.070	0.066
Czech	0.300	0.294	0.226	0.193	0.213	0.163	0.155	0.141	0.114
Denmark	0.014	0.014	0.012	0.013	0.010	0.010	0.009	0.008	0.009
France	0.023	0.023	0.021	0.023	0.020	0.016	0.015	0.015	0.014
Germany	0.026	0.023	0.021	0.022	0.018	0.016	0.015	0.014	0.013
Greece	0.020	0.018	0.015	0.021	0.021	0.023	0.022	0.019	0.021
Hungary	0.225	0.185	0.174	0.195	0.153	0.130	0.124	0.115	0.093
Ireland	0.035	0.034	0.034	0.024	0.019	0.019	0.014	0.013	0.015
Italy	0.022	0.020	0.019	0.019	0.020	0.044	0.020	0.021	0.021
Japan	0.013	0.011	0.011	0.009	0.010	0.011	0.011	0.010	0.009
Korea	0.074	0.085	0.090	0.082	0.065	0.054	0.043	0.036	0.029
Mexico	0.096	0.093	0.070	0.074	0.076	0.065	0.059	0.053	0.050
Netherlands	0.059	0.062	0.056	0.054	0.044	0.040	0.039	0.040	0.034
New Zealand	0.034	0.035	0.030	0.024	0.025	0.028	0.024	0.022	0.022

Norway	0.009	0.006	0.007	0.008	0.005	0.009	0.008	0.007	0.007
Poland	0.100	0.046	0.041	0.045	0.047	0.044	0.046	0.042	0.033
Portugal	0.029	0.029	0.030	0.031	0.039	0.043	0.046	0.039	0.038
Slovakia	0.444	0.475	0.336	0.285	0.231	0.212	0.158	0.107	0.120
Spain	0.018	0.018	0.020	0.022	0.025	0.026	0.027	0.030	0.028
Sweden	0.018	0.019	0.018	0.018	0.015	0.010	0.006	0.002	0.001
Switzerland	0.010	0.011	0.007	0.008	0.008	0.007	0.006	0.007	0.007
United Kingdom	0.030	0.029	0.028	0.028	0.026	0.024	0.020	0.018	0.017
United States	0.049	0.046	0.040	0.036	0.032	0.034	0.030	0.027	0.023
Argentina	0.061	0.048	0.049	0.046	0.043	0.043	0.049	0.049	0.046
Bolivia	0.119	0.150	0.166	0.162	0.166	0.141	0.147	0.156	0.178
Brazil	0.033	0.034	0.032	0.035	0.040	0.043	0.045	0.043	0.046
Chile	0.103	0.098	0.086	0.085	0.112	0.141	0.133	0.133	0.127
China	0.023	0.030	0.016	0.020	0.015	0.020	0.018	0.020	0.019
Cuba	0.143	0.123	0.105	0.106	0.093	0.104	0.080	0.073	0.063
Ecuador	0.088	0.085	0.082	0.095	0.081	0.090	0.101	0.087	0.065
Guatemala	0.042	0.048	0.051	0.057	0.060	0.055	0.049	0.055	0.052
India	0.061	0.063	0.051	0.073	0.066	0.055	0.047	0.046	0.048
Indonesia	0.098	0.077	0.070	0.066	0.054	0.107	0.106	0.081	0.064

Pakistan	0.115	0.137	0.131	0.128	0.126	0.120	0.112	0.120	0.123
Peru	0.047	0.042	0.037	0.048	0.039	0.046	0.040	0.038	0.034
Philippines	0.080	0.084	0.071	0.086	0.077	0.073	0.068	0.056	0.045
South Africa	0.030	0.031	0.025	0.027	0.027	0.023	0.017	0.017	0.026
Tanzania	0.119	0.110	0.097	0.103	0.093	0.089	0.077	0.077	0.075
Uruguay	0.031	0.032	0.026	0.029	0.030	0.031	0.027	0.031	0.026
Zimbabwe	0.013	0.020	0.027	0.022	0.021	0.005	0.010	0.008	0.013

I selected some countries and described their potential changes, according to their economic development (Figs. 2.13 and 2.14). In spite of national variations, I found that both OECD and non-OECD nations showed lower potential trends in CO_2 emissions over time. These can be interpreted to mean that the countries have enhanced their internal capability to improve production technical efficiency and therefore have produced good result to reduce the technological gap. However the PCII numerical values for many OECD countries were lower than those of non-OECD countries, indicating that OECD countries generally have had the smaller technological gap with the best practice than non-OECD nations. This means that they have enhanced their ability to ameliorate the energy efficiency paradox.

Among the OECD countries, Korea, in particular, made remarkable progress[15] in adopting efficient technologies related to energy usage. Among non-OECD countries,

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[15] The rate of progress is determined by the ratio of PCII (2006) to PCII (1990) in Table 6.

some countries such as Cuba, Philippines and Tanzania, made an effort to adopt more efficient production technologies. However, China and South Africa have lower potential for emission mitigation than Latin American, other non-OECD Asian, and even some OECD countries.

In the non-OECD group, China has lower potential to improve CO_2 intensity compared to most other non-OECD countries; this can be interpreted to mean that China has made an effort to adopt efficient technologies, and therefore, the relatively latest production technologies were introduced after opening the market. This result partially coincides with the result of Zhou and Ang (2008) who found that China has increased energy usage efficiency more than nations in other regions from 2002 to 2004.

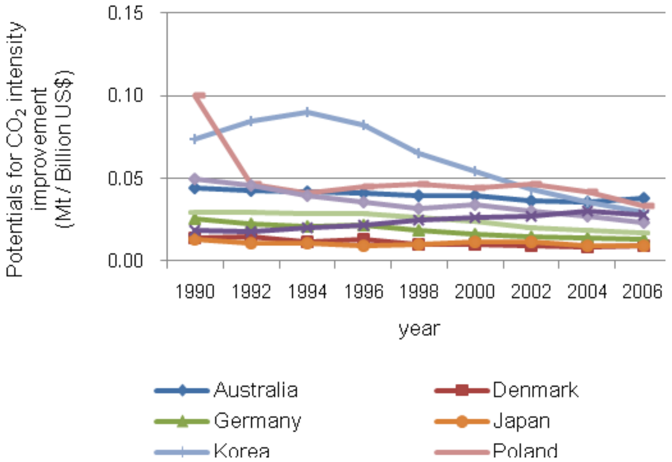

Figure 2.13. Relative potential for CO_2 intensity improvement for selected OECD countries

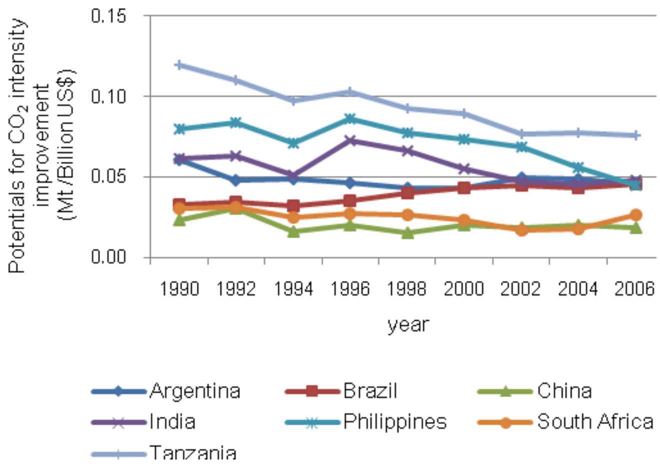

Figure 2.14. Relative potential for CO_2 intensity improvement for selected non-OECD countries

2.6 Conclusion

As global concerns about climate change increase, the need to control and mitigate GHG emissions is likely to emerge as a worldwide policy agenda. Therefore, the responsibility for emissions and the reduction level between countries has raised debate while few studies identifying the international emission trends and each country's mitigation potential have been undertaken. Decomposition is a useful method for identifying CO_2 emission trends and the impact of the driving forces behind the emissions; therefore, it can provide the fundamental basis for a global policy agenda for climate change.

With a production-based decomposition approach, I determined worldwide CO_2 emissions from the industry sector and analyzed opportunities to reduce CO_2 emissions. The production-based decomposition, our model, is expanded from the production-theoretical approach (Zhou and Ang 2008), which provides a base to integrate the environmental DEA framework into decomposition. Our model provides more detailed information about the influence of production technologies on CO_2 emissions and I can draw more explicit political implications (e.g., the potential for catching up in technical efficiency and technology innovation) from it.

Furthermore, I conducted a quantitative analysis for both the energy mix and the industrial structure impacts on CO_2 emission, the absence of which were noted as limitations in the Zhou and Ang (2008) study. I combined LMDI methodology with the

DEA framework using more disaggregated (sub- industrial) data. As a result of better measures of countries throughout the world, our model is significant because I can assess various driving forces on worldwide CO_2 emissions from industry and also provide clues to opportunities for reducing emissions.

For the empirical study, the changes of CO_2 emission for 26 OECD countries and 17 non-OECD countries during the period 1990-2006 were decomposed into six contributing factors. The decomposition results shows that, despite variations by country, the total CO_2 emissions generally decreases for OECD countries while they increased for non-OECD countries. Trends show that economic activity change has been the dominant contributor to the growth of CO_2 emissions while changes in potential energy intensity and energy mix have led to emission reduction in almost all OECD and non-OECD countries.

However, in many OECD countries, industrial structure changes have reduced CO_2 emissions, with a slight increase in the service sector and a decrease in the manufacturing sector. The change of industrial structure in non-OECD countries, however, shows a growing proportion of emissions from manufacturing but a declining one in service industries. This phenomenon led nearly one-half of all non-OECD countries to show increased CO_2 emissions. Developing Asian countries, such as China and India, have experienced greater industrial structure changes that have resulted in increasing CO_2 emissions.

In terms of production technology related to energy usage (i.e., technical efficiency and technological change), a mixed picture emerges, but it generally shows that technical performance has a weaker influence on CO_2 emission reduction than other underlying factors. I, nevertheless, need to inspect carefully the impact of production technology on emissions because it is very difficult to implement industrial structure reforms, and the improvement of technical efficiency and innovation for new technology are feasible at a reasonable cost.

Our analysis showed national variations in improving technical efficiency and developing the capability to innovate energy saving technology. In spite of these variations, I empirically show that northern and western Europe, OECD nations of Asia, and North America experience the energy efficiency paradox phenomenon (slow diffusion of the more advanced and effective technologies) less than other regions. I also show that many OECD countries have recently tried to enhance their capabilities for inventing new energy-saving technologies or absorbing external technologies, while other countries in eastern Europe and non-OECD regions have not innovated activities for new energy technologies until recently.

Furthermore, I analyzed each country’s relative potential for emission mitigation, and by measuring PCII between countries, I also accounted for the relative degree of energy efficiency paradox experienced by each. From this analysis, I determined that many OECD and non-OECD countries have experienced lower potential for mitigation over time. I can interpret these findings to mean that they have enhanced their internal capability to improve production technical efficiency.

The results, however, also show that OECD countries diffuse their production technologies more efficiently than non-OECD countries. This partially coincides with our decomposition result as mentioned above. I, therefore, point out the need for systemic advances of efficient technology for many countries experiencing the energy efficiency paradox. I also emphasize that research and development investment in production technology is needed to lower CO_2 emissions and to spread advanced technologies more actively through international cooperation.

Our study could have identified various contributors that are important factors in the IDA and PDA and drawn more conclusions and political implications. However, I also have some limitations on our proposed model. First, I consider only one input, i.e., energy consumption, although various factors such as labor, capital, and material are addressed. If I take more inputs to estimate the change of technical performance (i.e.,EUEEF and ESTEF), I can consider more alternative technologies and, therefore, induce more various implications. Second, many assumptions are required in the DEA analysis, e.g. CRS production technology set. For more accurate results, a more sophisticated DEA approach and more DMUs are needed. Third, I could not consider the structural change and the detail property in sub industries within each sector (e.g. the variation of carbon intensity) because I categorize the economy into three sectors of large scope. In further research, analysis by using detail information for sub industry can provide more specific explanations about industrial structure. In the future, if these limitations should be overcome, our study design will be able to provide more insights.

Chapter 3. Dynamics of Policy Impacts in Domestic Innovation System of Renewables Technology [16]

3.1 Introduction

In previous chapter, this thesis determines the impact of efficiency change and technological change in energy-use technology on CO_2 emissions and concludes that the efficient technology did not contribute to reduce CO_2 emissions in especially 1990s and many countries with non-OECD as the central figure still experience energy efficiency paradox despite improvement of paradox in OECD. This phenomenon is caused by potential market failure including information, institutions and unobserved cost, which is related to the diffusion process of technology (Jaffe and Stavins, 1994b). And it also offers basis for government to intervene the market and technological diffusion.

This phenomenon, as common attributes of diffusion process in clean energy technology, also occurs in renewable energy technology. As renewable energy technologies are receiving increasing global attention to address environmental concerns, renewable energy has seen a 30 to 40% growth rate in recent year (International Energy Agency [IEA], 2011a). However, demand for conventional energy has still outpaced

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[16] This chapter is based on the paper submitted to the journal of “Research Policy”. The title is “Dynamics of policy impacts on an endogenous technological-change system of renewable energy: Empirical analysis for solar photovoltaic and wind power technologies”.

demand for renewable energy, and second-generation[17] renewable-energy technologies, such those using wind and solar photovoltaic (PV) mechanisms, supplied less than 3% of the world's total electricity in 2009 (Renewable Energy Policy Network for the 21st Century [REN21], 2010). Also, most of the energy R&D budget in the world from 1974 to 2002 was expended on fossil fuel and nuclear energy (IEA, 2004).

Low R&D development and deployment of renewable energy technologies is the result of some market failures similar with energy-use technology. First, without a market price for pollutant abatements created through use of cleaner renewable energy, firms cannot produce profit with clean renewables and so invest in them at a less-than-socially optimal level (Jaffe et al., 2005; Popp, 2006; Pizer and Popp, 2008). Second, spillover from other firms' experience or knowledge allows companies to enjoy a free ride by gaining from others' experience and knowledge rather than investing in their own R&D. Due to the public-good nature of new knowledge, the investing firm cannot solely benefit from the accumulated knowledge created by its R&D effort and production (Jaffe et al., 2005). Furthermore, renewable energy technologies require huge capital investments for exploitation of the market, which is less competitive than the conventional-energy market, giving firms fewer motives for R&D investment and creating technological and market uncertainty.

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[17] According to the IEA (2006), renewable energy can be distinguished to three generations of technologies by levels of technical and market maturity. First-generation technologies, based on hydropower, biomass, and geothermal, have already reached the mature stage; second-generation technologies include those utilizing wind power, solar photovoltaic, and advanced bioenergy, which are growing rapidly; third-generation technologies use ocean energy, advanced geothermal, and concentrated solar power and are under development.

To moderate this market failure, various policies support technology progress and market expansion. In a technology push, many governments implement public R&D, private R&D, and combinations of subsidies as instruments to promote renewable-energy technology progress. In practice, the share of renewable energy technologies in the total government energy R&D budget has remained relatively stable and private R&D spending has grown gradually (IEA, 2006). To create market pull, governments have primarily introduced, with some variations, price-, quantity-, and tax-based instruments, among others, to encourage rapid diffusion of renewable energy (IEA, 2004).

Harmonization of these various incentive instruments would promote symmetric development of renewable energy technologies, which are considered the new growth engine for sustainable economic development because they are expected to resolve environmental concerns. The European Commission has tried to reinforce and bring together existing support schemes (Lauber, 2004). However, to harmonize renewable energy policies successfully, the performance of existing policies affecting the whole technological-change system, from invention to diffusion, must be assessed. Jaffe et al.(1999) stresses that it needs to understand the impact of policy over an entire technological progress process consists of invention, innovation, diffusion and technology use in order to evaluate the policy potential to resolve energy paradox and underinvestment for the clean energy technology.

Nevertheless, few studies address the performance of renewable energy policies, and the few that exist are based on theory or qualitative analysis (Menanteau et al., 2003;

Lauber, 2004; Foxon et al., 2005; Sagar and Zwaan, 2006; Butler and Neuhoff, 2008; Fischer and Newell, 2008). Some limited empirical analyses examined a relationship between policies and a partial technological-change system (e.g., innovation or diffusion) (Lanjouw and Mody, 1996; Buonanno et al., 2003; Popp, 2006; Söderholm and Klaassen, 2007; Pizer and Popp, 2008; Shafiei et al., 2009; Johnstone et al., 2010; Popp et al., 2011; Peters et al., 2012).

In this study, I model a whole technological-change system of renewable energy and empirically analyze the dynamics of renewable-energy policy impacts on this system. Because endogenous technological change can be provoked by supply and demand for technology, I determine primary technology-push as well as market-pull policies that lead to technological changes of renewable energy: *Public R&D* is the technology-push policy and *public investment, tariff incentives, renewables obligations*, and *environmental taxes* are the four market-pull policies reviewed. I focus on solar PV and wind power technologies used to generate electricity and generate estimates using unbalanced panel data of 16 countries that employed solar PV from 1992 to 2007 and 13 countries that accessed wind power from 1991 to 2006.

Specifically, I decompose the entire technological-change system of renewables into three component stages based on Schumpeter's study (1934) and study their interactions: *invention (R&D), innovation (cost reduction),* and *diffusion (deployment)*. I evaluate the *static* impact of the policies on each stage as well as simulated long-term *dynamic* impacts as the stages interrelate in a virtuous cycle.

The *static impact* refers to fixed and other stage-independent effects on each stage; the virtuous cycle of interactions between the three stages are not considered. In addition to direct effects of the policies on each stage, the dynamic impact reflects flexible and stage-dependent influences that exert indirect and additional effects as policies are circulated under interactions between the stages. For example, although renewables obligations are an instrument used to diffuse (deploy) technology through quotas, it may also affect invention and innovation. Therefore, one can estimate a direct and fixed effects of renewables obligations on each stage of static impact.

In endogenous technological change, if innovation (cost reduction) is stimulated by invention and diffusion, the direct impact of renewables obligations on innovation should be examined, and also I should its indirect impact on innovation via invention and diffusion (i.e., dynamic impact). The static impact assessment is important to understand the effect of policies on each stage accurately, and the dynamic impact in policy decisions is important to account for the interrelation between the stages such that the effect of policies is not underestimated.

In addition, by comparing solar PV and wind power technology, I provide a way to optimize policies for renewable energy technologies through phases of development maturity.[18] I distinguish the impact of international knowledge spillover from domestic knowledge externality, which helps to identify the linkage between domestic

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[18] Despite various renewable energy technologies, we analyze the second-generation renewable energy industry that has abundant technological and market potential and has grown rapidly to garner increasing global attention.

technological development and international knowledge transfer.

The remainder of this study is organized as follows: Section 3.2 relates background theories and related studies and Section 3.3 specifies our model based on previous research. In Section 3.4, I account for data used in this study. The results and discussion are presented in Section 3.5. Section 3.6 concludes this study.

3.2 Theoretical Background

3.2.1 The technological change system and learning effects

In this study, I consider that the technological change system of renewable energy consists of three main stages, based on Schumpeter's study (1934):[19] invention, innovation, and diffusion.

The first stage of technological change is invention created as a result of R&D activity and the consequent increase in knowledge stock can trigger innovation. Additionally, as knowledge accumulates, searching skills necessary for new knowledge improves due to increases in experience on acquiring *know-why*. The result of the learning-by-searching effect, know-why abilities accelerate the innovation process (Kamp et al., 2004), and some researchers have found that unit cost for a given technology responds to knowledge-accumulation experience (Kouvaritakis et al., 2000; Miketa and Schrattenholzer, 2004; Klaassen et al., 2005).

Market opportunities and learning effects that come from technological diffusion affect invention. Specifically, the more a technology diffuses, the more the market size increases and simultaneously the more competitive the market structure becomes, which leads a firm to invest more in R&D activity to increase expected profits and improve price competitiveness. Through the learning effect, increased diffusion of technology

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[19] Schumpeter (1934) researched technological progress and its economic implications. He suggested that the degree to which technology changes and comes into wide use depends on the three conditions of invention stage, innovation stage and diffusion stage.

creates more technology users whose feedback may promote invention. This learning-by-using effect involves experience through technology utilization and is based on the relationship between technology users and technology developers (Jaffe et al., 2005). The solutions for the complex components that are difficult to realize in development can be found by the *know-what* knowledge accumulated through increased use of technology (Kamp et al., 2004).

Innovation brings economic value to the invention and optimizes it for the market. Because innovation is difficult to observe, the consequences of it are measured and become synonymous with the innovation itself. Despite various outcomes of innovation, here I consider investment cost reduction for a given technology system because renewable energy technologies cost more than conventional technologies to generate electricity and because investment covers almost all the levelized cost of renewable energy, approximately 87%, on average, for solar PV and 75%, on average, for wind power (IEA-NEA-OCED, 2010), such that firms concentrate on reducing their investment cost for the system.

Many have tried to determine the relationship between cost reduction and several innovation-related factors, including technological progress, learning effects, economic incentives, and others (Isoard and Soria, 2001; McDonald and Schrattenholzer, 2001; Junginger et al., 2005; Popp, 2005; Kobos et al., 2006). Of particular interest, the impact of learning effects (from experience) on innovation (cost reduction) has been studied in a learning curve model. A conventional learning curve illustrates the relationship between cost reduction and output expansion such that production costs decrease as a result of cumulative production (Dutton and Thomas, 1984; Argote and Epple, 1990; Junginger et al., 2005). The relationship can be explained by a learning-by-doing effect that accounts for *know-how* accumulated by production experiences that improve production skill (Kamp et al., 2004). In recent years, researchers have analyzed the decline in cost by R&D activity as well as production experience using a two-factor learning curve (2FLC) model, based on the assumption that innovation is simultaneously induced by learning effects from diffusion (cumulative production) (i.e., learning-by-doing) and from invention (R&D activity) (i.e., learning-by-searching) (Kouvaritakis, 2000; Klaassen et al., 2005; Kobos et al., 2006).

The last stage is diffusion, which is based on market size and technological potential. Diffusion of renewable technologies is particularly important due to their role in mitigating long-term environmental externalities (Popp, 2005). Renewable technologies diffuse gradually, from the production side, learning-by-doing increasingly affects innovation (cost reduction), and from the consumption side, learning-by-using increasingly affects invention (R&D activity). Invention and innovation stimulated by cumulative experience (i.e., diffusion) can encourage additional renewable technology diffusion as the market improves and technological uncertainty is ameliorated. This dynamic series of effects can generate increasing returns of technology adoption (Jaffe et al., 2005).

When analyzing endogenous technological change, I should consider not only the invention stage in terms of start-point capacity but also the innovation and diffusion stages resulting from the market effects of the technological change. Furthermore, I should notice that each stage interacts with the others in complicated ways to create a virtuous cycle: The more technologies diffuse, the more the learning effects increase technological progress and accelerate cost reduction. The reduced cost encourages more technology diffusion, which completes the long-term virtuous cycle.

Some empirical evidence proves that each stage is affected by another stage. To determine the impact of invention (R&D activity) and diffusion (deployment) on renewable energy innovation, Klaassen et al. (2005) applied a 2FLC model in which cost reduction (innovation) is explained by the cumulative capacity (diffusion) and the R&D-based knowledge (invention) as they relate to wind power in Denmark, Germany and the United Kingdom. Through their empirical analysis, Klaassen found that innovation can be encouraged by learning-by-searching from R&D activity as well as learning-by-doing from diffusion. Söderholm and Klaassen (2007) researched interactions between innovation and diffusion stages using time series data of wind power for Denmark, Germany, Spain, and the United Kingdom. They identified a simultaneous relationship between innovation and diffusion such that cost reductions lead to increased diffusion, and this diffusion reduces investment cost via learning-by-doing effect. Meanwhile, Sagar and Zwaan (2006) focused on a link between R&D activity and diffusion and stressed that energy R&D activity is affected by learning and experience as engendered by technological deployment. These studies, however, identify learning effects for only one aspect of the technological change system without describing the overall effects of each interaction. In Section 3.3, I discuss the endogenous technological-change system in terms of the encompassing effects of interactions between invention, innovation, and diffusion.

3.2.2 Impacts of renewable energy–related policies

In this study, I consider public R&D, as a representative technology-push policy, and public investment, tariff incentives, renewables obligations, and environmental taxes, as four market-pull policies, as the primary players involved in the technological change system of renewable energy.

Public R&D is supported by government finances. It is conducted by foundations, private firms (for commercial uses), and public institutions. While technology-push policy focuses on invention, market-pull policies are directed toward reducing cost and increasing demand and deploying renewable energy (Nemet, 2009). The public investment, which is implemented in various ways, can be regarded as government support for expanding the market. In this study, I limit the concept of public investment to government procurement for electricity generated by renewable energy and to government subsidies for installation of facilities, infrastructures, and systems. The tariff incentives, including feed-in tariff (FIT) and guaranteed prices, indicate that electric utilities should purchase renewable electricity at a premium price, which is paid by consumers or supported by government subsidies (Lauber, 2004). The renewables obligations include a renewable portfolio standard (RPS) and a renewable quota on electricity suppliers such that they must offer a certain percentage of consumable electric energy from renewable sources. Authorities impose a bidding process organized to garner the cheapest option (Lauber, 2004). Environmental taxes are considered the simplest and most efficient solution for correcting market imperfections (Menanteau et al., 2003), and they are used to impose renewable energy technologies by raising the costs of fossil fuel or GHG emissions pricing.

In this study, I classify market-pull policies mostly into price-based, quantity-based, and environmental policies by support schemes. The price-based policy includes tariff incentives because they guarantee technology-specific premium prices. The quantity-based policy includes renewables obligations, which sets the renewables electricity quota. The environmental policy includes taxes that can indirectly affect the renewable energy system.

These policies are instrumental for government intervention in the renewable energy market in efforts to resolve market failure, but their impacts on the whole technological-change system may vary. Recently, harmonization of these policies has received growing attention as policy makers look for symmetric development of technologies by maturity level as well as enhancement of policy efficiency.

Many have researched energy and environmental policies that affect technological change of renewable energy. Some studies stress the importance of public R&D in the endogenous change of energy-related technology because it can provide incentives for creating new ideas by compensating for a firm's underinvestment resulting from technological uncertainty, market imperfections, and failure in the knowledge market (Popp, 2005; Pizer and Popp, 2008; Aschhoff and Sofka, 2009). Goulder and Parry (2008) emphasized that the combination of basic government research and demonstration projects can restore invention efforts by reducing appropriability problems.

The market-pull policies can also indirectly affect the invention stage. The various policies serve as incentives to promote R&D activity by reducing market uncertainty, but they have different effects on renewable energy invention in situations where information is imperfect and uncertainty exists (Menanteau et al., 2003).

Although opinions vary about the impact of policies on invention (R&D), the price-based policy (e.g. FIT) is more likely to promote R&D activity than the quantity-based policy (e.g. RPS) because the former enables producers to pursue additional profits by R&D activity due to the guaranteed price, whereas the profits incurred by the latter policy benefits consumers due to the competitive price (Lauber, 2004; Butler and Neuhoff, 2008).

Furthermore, using patent data from 25 countries, Johnstone et al. (2010) analyzed the impact of policies, including government R&D initiatives, renewable energy certificates, FITs, capital grants, renewables obligations, and tax exemptions on the invention of various renewable energy technologies. They found that FIT has a positive and significant effect on invention for high cost technology such as solar energy, whereas renewable energy certificates and renewables obligations expert positive and significant impacts on low cost technology such as wind power. These results suggest that policy effectiveness depends on the maturity of the technology. Peters et al. (2012), also with patent data, determined the impacts of domestic technology-push and demand-pull policies and the effects by spillover of foreign policies on domestic invention. They found that technology-push policies could not create significant country-level spillover, whereas demand-pull policies could foster invention outside as well as inside national borders. However, their analysis was limited because they measured demand-pull policies using capacity additions as proxies.

Many studies focus on the policy impacts on cost reduction. The general opinion has emerged that use of the quantity-based policy is more appropriate to bring down the price of renewable energies than the price-based policy because the former reserves some renewable energy and allows consumers to choose the cheapest options, while the latter does not provide producers with incentives to reduce their prices for consumers. Determining wind power in Denmark, Germany and the United Kingdom, Ibenholt (2002) provided empirical results suggesting that the quantity-based policy induces more cost reduction than the price-based policy does because it orchestrates competitive prices between renewable energy producers. According to Lauber (2004), RPS schemes are more efficient means for reducing price, but the high pressure they create to reduce costs also discourages renewable producers from investing in R&D. Söderholm and Klaassen (2007) determined the impact of FIT schemes on innovation of wind power in some

European countries by modeling the simultaneous link between investment cost and diffusion. They identified FIT as positively correlated with investment cost, and they determined that wind power producers have few incentives to reduce cost and therefore choose high-cost sites.

Opinions about the impact of policies on efficient renewable-energy technology diffusion are mixed. Some suggest that RPS schemes have relatively little impact on expanding renewable energy due to the high risk of investment, although they obligate consumption of renewable energy toward renewable energy consumers (Rowland, 2005; Ringel, 2006; Mitchell et al., 2006). Others point out that FIT can result in more installed capacity because guaranteed prices offer better predictability and enable safer investments (Ibenholt, 2002; Menanteau et al., 2003). Meyer (2003) stressed that renewable energy usage can increase via FIT schemes that make capital financing easier, whereas a green-certificate trading system based on quotas for renewable energy usage may cause uncertainty for investment as well as high transaction costs due to competition. Other studies illustrate that RPS schemes not only create undramatic variations of installed capacity through fixed goals but also enable stable growth with a predictable schedule (Rader and Hempling, 2001; Lauber, 2004). RPS schemes can play a role in creating consumer interest in renewable energy (Langniss and Wiser, 2003).

In addressing the development of various technologies, Unger and Ahlgren (2005) pointed out that quantity-based policies may hamper the symmetric development of technologies with different maturity levels because renewable energy consumers choose the cheapest options in the bidding system. In Texas, for example, solar PV and traditional biomass technologies are too costly to compete with wind power, although the successful expansion of renewable energy was achieved by RPS schemes (Langniss and Wiser, 2003).

While lively arguments for specific policy impacts on technological-change systems continue, previous literature offers a fragmented picture by showing the impact of policies on one part of a system but not considering the dynamic interplay of polices over the whole system. In fact, very few studies offer empirical analysis for policies within the entire system for endogenous technological change.

In this study, I assess the dynamic impact of several policies by building the simultaneous linkages among the invention, innovation, and diffusion stages. In so doing, I explain the mechanisms by which specific policies successfully affect change in renewable energy technologies.

3.3 Simultaneous Equations

3.3.1 Invention model: new idea production by technological learning and knowledge spillovers

Inventions or new ideas are regarded as one of endogenous factors for economic growth with labor and capital in earnest since Romer (1990)’s endogenous growth model. Jones and Williams (1998) suggested the theoretical framework for new idea produced by resources devoted to R&D and knowledge stock, and they modeled undepreciated R&D stock as endogenous factor for economic growth.

On the other hand, Sørensen et al. (2003) established semi-endogenous growth model considering depreciation of R&D activity which causes the needs of public innovation support system (e.g. public R&D, education and subsidies) for long-term technological progress. Invention model in this study is motivated by the new idea function from the studies of Jones and Williams (1998) and Sørensen et al. (2003).

R&D investment of technology *i* for country *n* in time *t* is modeled as a function of the level of technological diffusion, the level of government support for R&D (i.e., public R&D budget) and other factors devoted to R&D as following log-linear model, Eq. (3-1):

$$RI_{i,n,t} = X_{i,n,t} \cdot CC^{\theta}_{i,n,t} \cdot GS^{\xi}_{i,n,t} \tag{3-1}$$

where $RI_{i,n,t}$ represents R&D investment, $CC_{i,n,t}$ is technological diffusion, $GS_{i,n,t}$ is government support for R&D and $X_{i,n,t}$ is further determinants for R&D such as science resource and renewable energy-related policies.

The production of new ideas for technology *i* is specified according to a certain production function *G* with respect to R&D investment and knowledge stock:

$$Z_{i,n,t} = G(RI_{i,n,t},\ KS_{i,n,t-1}) \tag{3-2}$$

where $Z_{i,n,t}$ is invention or new idea, and $KS_{i,n,t-1}$ is the previous knowledge stock, which are measured by patent data. I consider that there is a time lag between $Z_{i,n,t}$ and $KS_{i,n,t-1}$ because knowledge stock in time *t* also includes invention in time *t* as described below. In Eq. (3-2), I assume that production function *G* is increasing, which means that more R&D leads more invention. This assumption is appropriate because this study determines the second-generation technologies, solar PV and wind power, which are recently developing and widespread. Regarding function *G* as the special case of the Cobb-Douglas function, I establish the invention model as Eq. (3-3):

$$Z_{i,n,t} = CC_{i,n,t}^{\alpha_1\theta} \cdot GS_{i,n,t}^{\alpha_1\xi} \cdot X_{i,n,t}^{\alpha_1} \cdot KS_{i,n,t-1}^{\alpha_2} \tag{3-3}$$

The knowledge stock is subdivided into the overseas and the domestic knowledge stock categories to enable one to distinguish which spillovers are more effective on invention and innovation. Identification of the spillover source is important for creating open innovation strategies for renewable energy technologies in the early stage of development and when markets are increasingly competitive.

In this study, I model the domestic knowledge stock reflecting depreciation and diffusion of past patents, based on Popp (2001)'s study, as follows:

$$DKS_{i,n,t} = \sum_{s=0}^{p} e^{-\gamma_1 s} \cdot (1 - e^{-\gamma_2 (s+1)}) \cdot PA_{i,n,t-s} \tag{3-4}$$

where $DKS_{i,n,t}$ represents the domestic knowledge stock of technology i for country n in time t, $PA_{i,n,t}$ is the number of patent applications related to renewable technologies, and s is an index of years from the past, p, to the present, t. The parameters γ_1 and γ_2 indicate depreciation and diffusion rates, respectively. I use the mean values as estimated by Popp (2001): depreciation rate = 0.44 and diffusion rate = 2.97. Eq.(3-2) shows that knowledge stock proceeds with widespread diffusion and increased obsolescence as time passes.

In explaining overseas knowledge stock, Buonanno et al. (2003) and Bosetti et al. (2008) simply described the undepreciated stock of world knowledge as a summation of each country's own stock, whereas I build the overseas knowledge stock considering rates of depreciation and diffusion. First, the overseas knowledge pool is modeled by summing patent applications of all countries except country n, and second, the overseas knowledge stock is specified by considering diffusion and obsolescence of stock as follows:

$$OKS_{i,n,t} = \sum_{s=0}^{p} e^{-\gamma_1 s} \cdot (1 - e^{-\gamma_2 (s+1)}) \cdot (\sum\nolimits_{j \neq n} PA_{i,j,t-s}) \tag{3-5}$$

where $OKS_{i,n,t}$ is the overseas knowledge stock, and the last term of right side in Eq. (3-5) means the knowledge pool that consists of the rest j countries' patent applications except country n. The superscripts and subscripts in Eq. (3-5) are identical with Eq. (3-4). I assume a time lag between invention and knowledge stocks because knowledge stock in time t also includes invention in time t.

Various policies implemented by government play important roles in managing supply and demand for renewable energy technologies over their life cycle. In our model, I assume that market-pull policies have direct and indirect impacts on the whole technological-change system (i.e., all three stages), whereas technology-push policies have direct impact only on the development of technology (i.e., invention stage). The technology-push policy (i.e., public R&D) works as an input of invention, and furthermore, it plays a role in compensating for underinvestment of private R&D, correcting negative knowledge externality or the crowding out of private firms. The market-pull policies are more widespread in the technological change system, contributing rapid economy of scale and efficient market structure as well as resolving market and knowledge failure by institutional instruments as well as subsidies. These contributions of market-pull policies can result in a change from invention to diffusion for technologies.

Based on these models, I introduce a log-linear equation for econometric specification as follows:

$$\begin{aligned}\ln Z_{i,n,t} = a_0 &+ a_1 \ln CC_{i,n,t} + a_2 \ln DKS_{i,n,t-1} + a_3 \ln OKS_{i,n,t-1} \\ &+ a_4 \ln TP_{i,n,t} + a_5 \ln MP_{i,n,t} + a_6 \ln SR_{n,t} + \mu_{i,n,t}\end{aligned} \qquad (3\text{-}6)$$

where $TP_{i,n,t}$ represents technology-push policy, $MP_{i,n,t}$ is market-pull policies, and $SR_{i,n,t}$ is scientific resource which both are included by other factors affecting inventions (i.e., $X_{i,n,t}$). Lastly, $\mu_{i,n,t}$ is the error term.

R&D activity is increased by more learning-by-using (i.e., new requirements from consumers or stakeholders) as acquired from increases in diffusion of technologies. This uptick in R&D results in more inventions ($a_1 > 0$). I calculate the learning-by-using rate as $1-2^{-a_1}$ to show constant increases in invention for each doubling of diffusion (cumulative capacity).

The coefficients of a_2 and a_3 show whether knowledge externality from previous knowledge stock affects inventions or not. If each coefficient has positive sign, domestic and overseas knowledge spillover from the previous knowledge stock has positive knowledge externality on invention. In addition, with the coefficient of a_4 , I can identify whether the technology-push policy acts complementary to or as a substitute of private R&D.

3.3.2 Innovation model: two-factor learning curves

In this study, I regard innovation as a system-cost reduction and build an innovation model based on 2FLC. The 2FLC can account for the learning-by-searching as well as the learning-by-doing effect on innovation. Eq.(3-7) describes a model that shows that the per-unit installed system cost of technology i for country n in time t ($SC_{i,n,t}$) is affected by technological diffusion ($CC_{i,n,t}$), two knowledge stock terms ($DKS_{i,n,t}$ and $OKS_{i,n,t}$), and market-pull policies($MP_{i,n,t}$):

$$SC_{i,n,t} = A \cdot CC_{i,n,t}^{\beta_1} \cdot (DKS_{i,n,t}^{\lambda_1} \cdot OKS_{i,n,t}^{\lambda_2 + \lambda_3 ACAP_{i,n,t}})^{\beta_2} \cdot MP_{i,n,t}^{\beta_3} \qquad (3\text{-}7)$$

where A is a further determinant that affects the cost of renewable energy technology.

In the innovation model, I also consider two sources of knowledge stock, domestic and overseas, to identify the more specific impact of learning-by-searching. I assume that learning-by-searching effects are proportional to accumulation of knowledge. If $\beta_2 < 0$, a declined system cost can be explained by learning-by-searching, but if $\beta_2 > 0$, the increased knowledge stock engenders high social cost required to maintain the knowledge stock and thus increases system stock. The learning effects from two knowledge stocks depend on the maturity of the technological development as well as common market conditions.

In addition, learning effects from overseas knowledge stock depend on the level of *absorption capacity*,[20] which refers to the ability of external knowledge to fit internal conditions for innovation. Absorption capacity is enhanced by various experiences as well as R&D efforts and varying quantitative and qualitative differences in the impact of foreign knowledge on domestic innovation. Many studies about R&D and innovation consider absorption capacity an important factor that needs to be investigated for an accurate assessment of R&D results (Cohen and Levinthal, 1989; Griffith et al., 2003; Kneller, 2005). Based on Bosetti et al. (2008), I describe the absorption capacity ($ACAP_{i,n,t}$) that is represented by the ratio of one country's domestic knowledge stock to total knowledge stock made up from all analysis objectives as follows:

$$ACAP_{i,n,t} = \frac{DKS_{i,n,t}}{\sum_{j \in N} DKS_{i,j,t}} \tag{3-8}$$

where N is a group of analysis objectives. Eq.(3-8) shows that the more one country accumulates domestic knowledge stock, the more it is able to absorb foreign knowledge and internalize it.

Meanwhile, market-pull policies are important determinants on the system cost for renewable energy because they play a dominant role, including reallocation of production resources, adjustment of supply and demand, and reform of market structure, in resolving the inherent failure in the renewable energy market.

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[20] Although the effect of absorption capacity can be specified in an invention model, we determined this effect in the innovation model to analyze more thoroughly the ultimate effect of absorption capacity.

In this study, I consider two kinds of further determinants. First, raw material price is considerable because system costs may increase in proportion to the rise in raw material price. For example, Swanson (2006) stressed that the price of silicon is one of major factors affecting production of solar PV facilities. Second, the cost for installation of the system depends on infrastructure development and production ability, and therefore, it is appropriate to measure each country's gross domestic products (GDP) as the level of such development and ability.

I describe the following reduced-form equation by taking natural logarithms:

$$\begin{aligned}\ln SC_{i,n,t} = b_0 + b_1 \ln CC_{i,n,t} + b_2 \ln DKS_{i,n,t} + (b_3 + b_4 ACAP_{i,n,t}) \ln OKS_{i,n,t} \\ + b_5 \ln MP_{i,n,t} + b_6 \ln RMP_{i,t} + b_7 \ln GDP_{n,t} + \varepsilon_{i,n,t}\end{aligned}$$

(3-9)

where $RMP_{i,t}$, $GDP_{n,t}$, and $\varepsilon_{i,n,t}$ represent the variables of raw material price, development of infrastructure and production ability, and an error term, respectively. In Eq.(3-9), I obtain the learning-by-doing rate ($1-2^{b_1}$) and the learning-by-searching rate ($1-2^{b_2}$). The more technology is developed and diffused, the more innovative and efficient the simultaneous results.

3.3.3 Diffusion model: profit maximization for rational choice

Diffusion model in this study is derived by a modified rational choice model based on Söderholm and Klaassen (2007). Assuming that producers of renewable energy pursue profit maximization, I model total benefit accomplished by adopting renewable energy technology *i* for country *n* in time *t*:

$$TB_{i,n,t} = K_{i,n,t} \cdot CC_{i,n,t}^{\delta_1} \cdot \left(\int_0^T REP_{i,n,t} e^{-rt} dt\right)^{\delta_2} \cdot \left(\int_0^T FFP_{n,t} e^{-rt} dt\right)^{\delta_3} \qquad (3\text{-}10)$$

where $TB_{i,n,t}$ represents the total benefit, $REP_{i,n,t}$ is on-grid price of renewable energy technology *i*, $FFP_{n,t}$ is a price of fossil fuels for electricity generation assumed as fixed value over technology *i* and $K_{i,n,t}$ is other factors to affect the total benefit of renewable energy.

This study chooses log-linear form similar to the one of Söderholm and Klaassen (2007) for easy derivation of differentiation in profit maximization. Eq. (3-10) explains that the expected total benefit depends on the relation between cumulative capacity ($CC_{i,n,t}$) and market price of renewable energy ($REP_{i,n,t}$). In addition, the increased price of fossil fuels ($FFP_{n,t}$) may have positive impact on increase of total benefit for renewable energy because renewable energy technologies can be regarded as substitutional goods for fossil fuels. If I assume that market price of renewable energy is set by its cost for installation of system ($SC_{i,n,t}$) and market pull policies ($RP_{i,n,t}$) dominantly, Eq. (3-10) is modified as follows:

$$TB_{i,n,t} = K_{i,n,t} \cdot CC_{i,n,t}^{\delta_1} \cdot \left[\int_0^T (RP_{i,n,t}^{\eta_1} \cdot SC_{i,n,t}^{\eta_2}) e^{-rt} dt \right]^{\delta_2} \cdot (\int_0^T FFP_{n,t} e^{-rt} dt)^{\delta_3} \tag{3-11}$$

In addition, it is worth considering total amount of electricity generation as one of further determinants ($K_{i,n,t}$) to affect total benefit of renewable energy in order to reflect economy of scale for electricity market. The larger scale of electricity market is, the more demand of renewable electricity arises, and therefore it may affect the total benefit of renewable energy.

Eq. (3-12) describes the total cost ($TC_{i,n,t}$) for adopting renewable energy technology *i* for country *n* in time *t* given their cumulative capacity ($CC_{i,n,t}$) and per-unit system cost ($SC_{i,n,t}$):

$$TC_{i,n,t} = C_0 \cdot (CC_{i,n,t})^{\omega_1} (SC_{i,n,t})^{\omega_2} \tag{3-12}$$

According to renewable energy producers' profit maximization for rational choice, the marginal benefit is identical with the marginal cost, which marginal values of them are derived by differentiation of Eq.(3-11) and Eq.(3-12) with respect to cumulative capacity ($CC_{i,n,t}$). The first-order condition for profit maximization can be specified as follows:

$$\frac{\partial TB_{i,n,t}}{\partial CC_{i,n,t}} = \frac{\partial TC_{i,n,t}}{\partial CC_{i,n,t}}$$

(3-13)

$$\Leftrightarrow K_0 \cdot K_{i,n,t} \cdot \delta_1 (CC_{i,n,t})^{\delta_1 - 1} \cdot (RP_{i,n,t})^{\eta_1 \delta_2} \cdot (SC_{i,n,t})^{\eta_2 \delta_2} \cdot (FFP_{i,n,t})^{\delta_3}$$
$$= C_0 \cdot \omega_1 (CC_{i,n,t})^{\omega_1 - 1} \cdot (SC_{i,n,t})^{\omega_2}$$

I establish econometric-form for diffusion model by taking natural logarithms after rearranging Eq.(3-13) by $CC_{i,n,t}$:

$$\ln CC_{i,n,t} = c_0 + c_1 \ln SC_{i,n,t} + c_2 \ln MP_{i,n,t} + c_3 \ln FFP_{n,t} + c_4 \ln TEG_{n,t} + \tau_{i,n,t}$$

(3-14)

where $MP_{i,n,t}$ represents market-pull policies, $TEG_{n,t}$ is total amount of electricity generation as further determinant to affect total benefit and $\tau_{i,n,t}$ is error term.

3.3.4 Interactions between simultaneous equations

As shown in Eq.(3-6), (3-9), and (3-14), I build an endogenous technological change model that enables one to know the simultaneous interactions between invention, innovation, and diffusion as well as the effects of several determinants, including renewable energy-related policies, on these stages.

Fig. 3.1 shows that renewable energy technologies are able to progress within a long-term virtuous cycle that is triggered by renewable energy-related policies. This virtuous cycle can be explained by systematic processes.

The market-pull policies create an initial market to introduce renewable technology, and technology-push policies allow producers to overcome technological barriers more easily. Diffusion of renewable technologies through market expansion lowers the system cost (i.e., innovation) of renewable energy by production and R&D learning effects. To account for this, diffusion of renewable technologies must increase production simultaneously with consumption (i.e., increased cumulative installation capacity accounts for a simultaneous expansion of production and consumption scales), a consideration based on the assumption that all renewable energies produced in a country are fully consumed in its market.

As production of renewable energy increases, the more learning-by-doing can positively influence cost reduction measures. With knowledge spillover from previous domestic and overseas knowledge stock, the more learning-by-using by increased diffusion (consumption) can positively exert power on R&D activity, which results in the accumulation of organized knowledge stock and lowers the cost as it initiates more learning-by-searching. At the innovation step (i.e., cost reduction) these learning effects lead to increased diffusion of technologies by enhancing the price competitiveness and reducing technical uncertainty. As a result, the more technologies diffuse, the more learning effects abound and the technological progress is accelerated by this virtuous cycle.

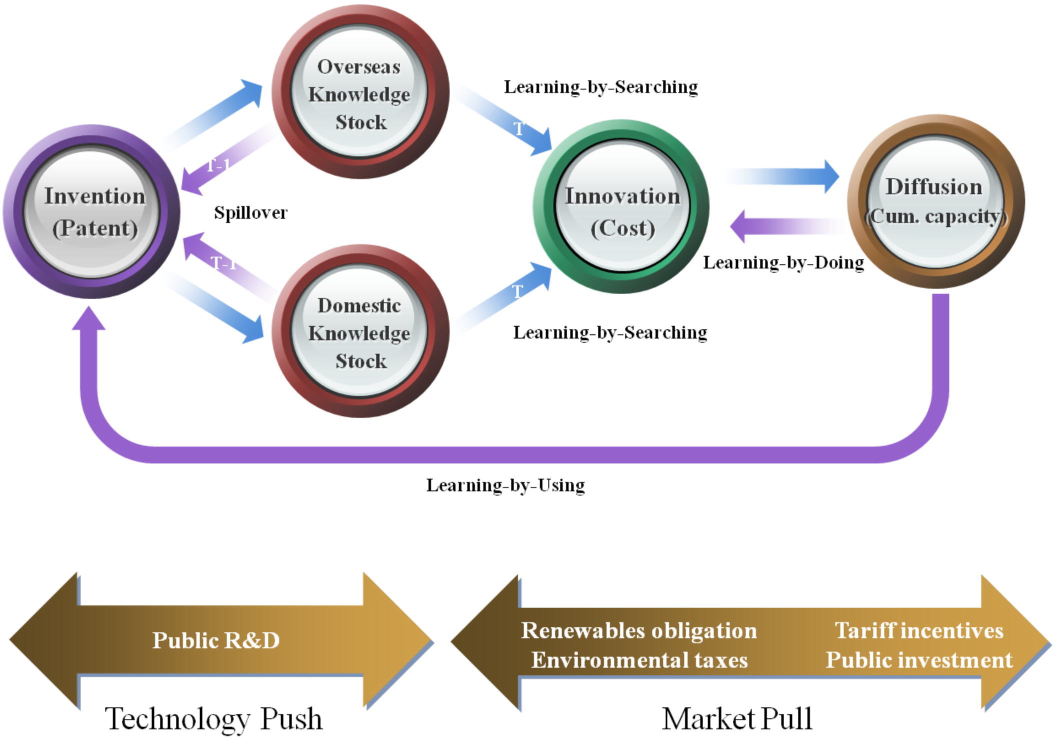


Figure 3.1. Endogenous technological change based on the learning mechanisms and renewable energy-related policies.

3.4 Data and Model Estimation

For our analysis, I chose some Organisation for Economic Cooperation and Development (OECD) countries included in the Annex II group. These nations are obligated to offer technology transfer and loan support to developing countries if clean technologies, such as for renewable energy, can be viably introduced and diffused, either by the country's vested interest or due to global regulations. Sixteen countries were studied in regard to solar PV: Australia, Austria, Canada, Denmark, France, Germany, Italy, Japan, Korea, the Netherlands, Norway, Spain, Sweden, Switzerland, the United Kingdom, and the United states; Thirteen countries were studied in regard to wind power: Canada, Denmark, Finland, Germany, Italy, Japan, the Netherlands, Norway, Spain, Sweden, Switzerland, the United Kingdom, and the United states. Various data for these countries were collected from 1992 to 2007 for solar PV and from 1991 to 2006 for wind power, but details of the time series depends on country, which makes for unbalanced panel data with a time gap.

3.4.1 Dependent variables

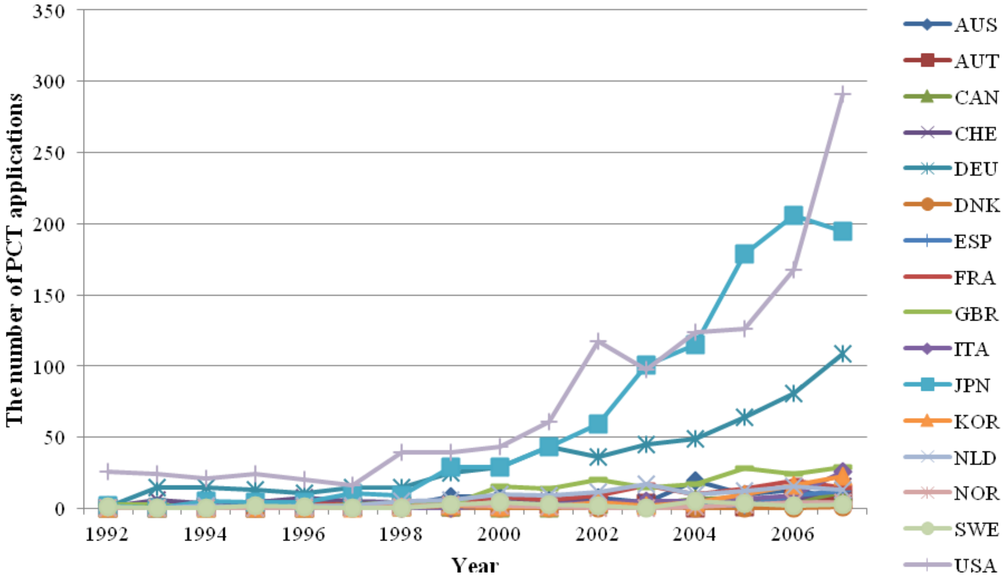
In three econometric equations, Eq.(3-6), (3-9), and (3-14), I assume that the proportion of patent applications of renewable technology to the total patent application, installed system cost, and cumulative capacity represent invention ($Z_{i,n,t}$), innovation

($SC_{i,n,t}$), and diffusion ($CC_{i,n,t}$), respectively.

For measuring invention ($Z_{i,n,t}$), I use patent data. Recently, patents have received increasing attention as the outcomes of invention or R&D activity, and some studies have found empirical evidence that environment and energy-related policies affect patent activity (Jaffe and Palmer, 1997; Brunnermeier and Cohen, 2003; Popp, 2006; Johnstone et al., 2010). Patent information is useful due to its wide availability, specific data by technology, and easy measure of diffusion of the invention. Therefore, economists regard patents as good indicators of R&D activity (Popp, 2006).

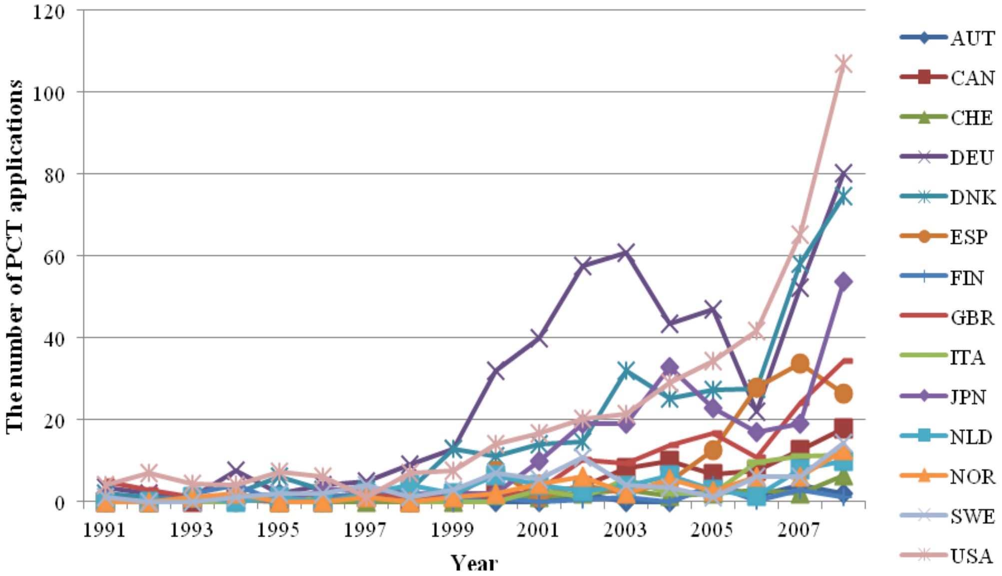
Specifically, patent applications filed under the Patent Cooperation Treaty (PCT) are counted by the inventor's country of residence and application date. Although PCT applications provide less data for estimation than patent applications filed under a domestic patent office, they have several advantages for the researcher, including less home bias, less variation of patent quality, and an easy-to-access collection of patent applications. I collected these data from the OECD's iLibrary database (2011a), which provides information about patent applications in environmental-related technologies, wind energy, and solar PV energy filed under PCT.

Figs. 3.2 and 3.3 show trends of PCT application in solar PV and wind power, respectively. From these figures, one can find that most of countries have experienced an increased filing for renewable energy patents through PCT. The patent applications of two technologies experienced rapid growth before and after 2005 when mandates from the 1997 Kyoto protocol were introduced and took effect. Of the countries studied, Germany, Japan, and the United States show the most PCT applications for solar PV, and Denmark, Germany, and the United States show the most PCT applications for wind power.



Note: AUS=Australia, AUT=Austria, CAN=Canada, CHE=Switzerland, DEU=Germany, DNK=Denmark, ESP=Spain, FRA=France, GBR=the United Kingdom, ITA=Italy, JPN=Japan, KOR=Korea, NLD=the Netherlands, NOR=Norway, SWE=Sweden, USA=the United States

Figure 3.2. PCT applications of solar PV



Note: AUT=Austria, CAN=Canada, CHE=Switzerland, DEU=Germany, DNK=Denmark, ESP=Spain, FIN=Finland, GBR=the United Kingdom, ITA=Italy, JPN=Japan, NLD=the Netherlands, NOR=Norway, SWE=Sweden, USA=the United States

Figure 3.3. PCT applications of wind power

For a dependent variable of innovation (cost) ($SC_{i,n,t}$), I introduce different instrument variables to represent per-unit installed system cost (US$/kW) for solar PV and wind power due to the difficult availability of cost data for each technology as well as the different data sources available. The installed system cost for solar PV technology is represented by the prices (US$/kW) for the entire solar PV system including module, battery, and mounting structure, and more specifically, system prices for on-grid applications using fewer than 10kW. I constrained our data collection to on-grid applications to reduce variation by location, size, and customers that resulted from off-grid applications and to collect more data. These system price data were drawn from national survey reports submitted to the Photovoltaic Power Systems Programme (PVPS) and survey reports annually published by IEA-PVPS (1992 – 2008).[21]

For wind power, the average investment costs (US$/kW) are based on installed system costs as found in specific issue of *Wind Energy Annual Report* published by the IEA (1992-2008), De Noord et al. (2004), and Wiser and Bolinger (2008). For solar PV prices and wind power cost, I converted national currency data using U.S. dollar exchange rates and deflated them to constant 2000 prices using GDP deflators.[22]

Figs. 3.4 and 3.5 display time variances of system prices of solar PV and investment costs of wind power, which both illustrate declining trends during the 1990s. Since 2000, however, most system prices of solar PV vary little over time, whereas investment costs of wind power, far from a declining trend, show steep growth. According to the *Wind Energy Annual Report* (2006) published by the IEA, this result is caused by a post-2000 rapid increase in raw material prices, particularly steel, which is used to construct the wind-energy mechanisms. In addition, a short supply of wind power components caused by large demand of wind energy and reinforcement of Low Voltage Ride Through

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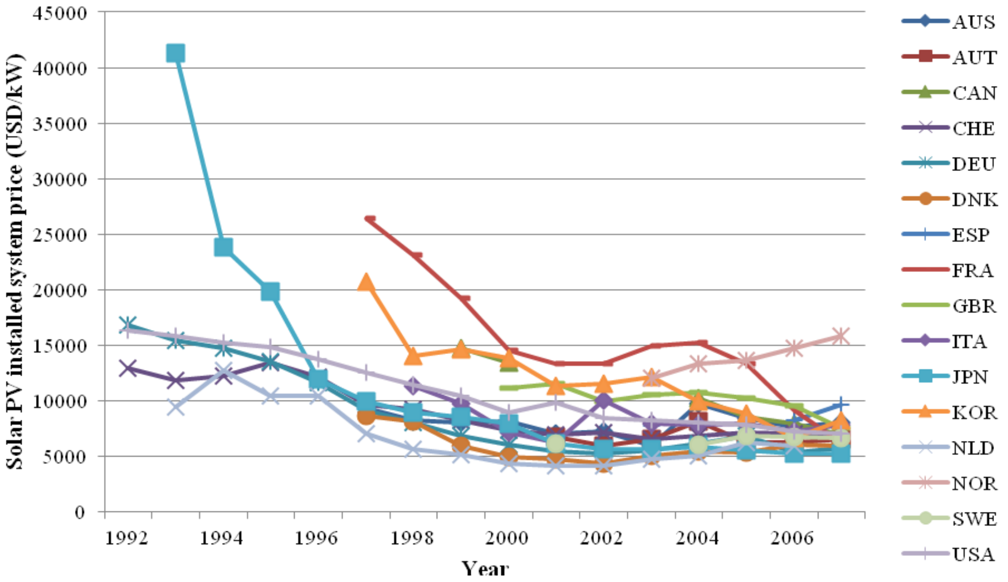
[21] This study refers to the national survey report of PV power applications for Australia (2002), Canada (2005), Denmark (2003), Germany (2002), France (2007), Italy (2003), Japan (2006), Korea (2002), Switzerland (2002), and the United States (2002), and *Trends in Photovoltaic Applications* annually published by IEA-PVPS from 1992 to 2008.

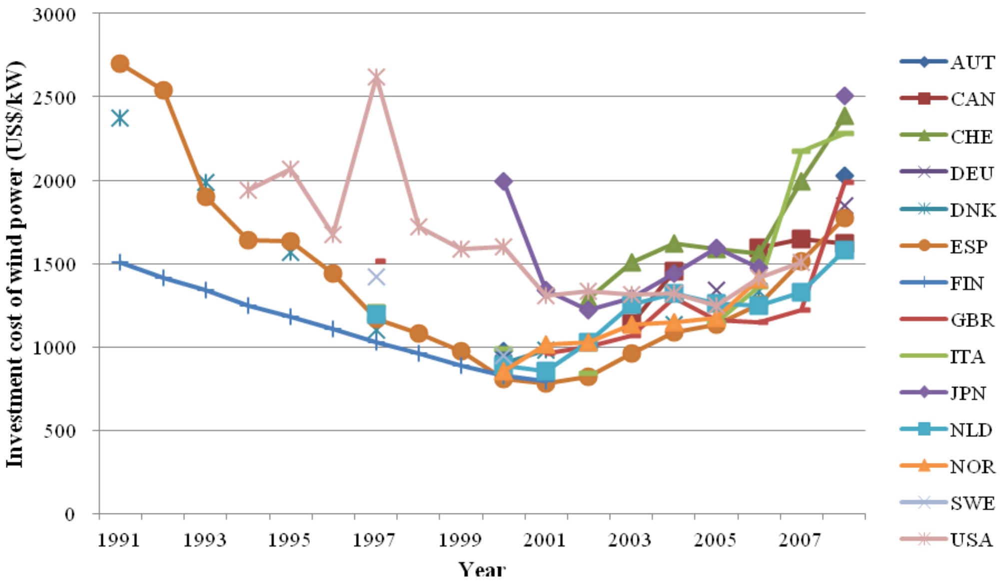
[22] The exchange rates and GDP deflators are provided by the on-line database *OECD iLibrary* (http://www.oecd-ilibrary.org/statistics).

technology, which enables wind power plants to operate stably during sudden voltage changes, have been major factors raising investment costs in wind power.



Note: AUS=Australia, AUT=Austria, CAN=Canada, CHE=Switzerland, DEU=Germany, DNK=Denmark, ESP=Spain, FRA=France, GBR=the United Kingdom, ITA=Italy, JPN=Japan, KOR=Korea, NLD=Netherlands, NOR=Norway, SWE=Sweden, USA=the United States

Figure 3.4. Installed system price of solar PV up to 10kW on grid, US$/kW (2000 prices)



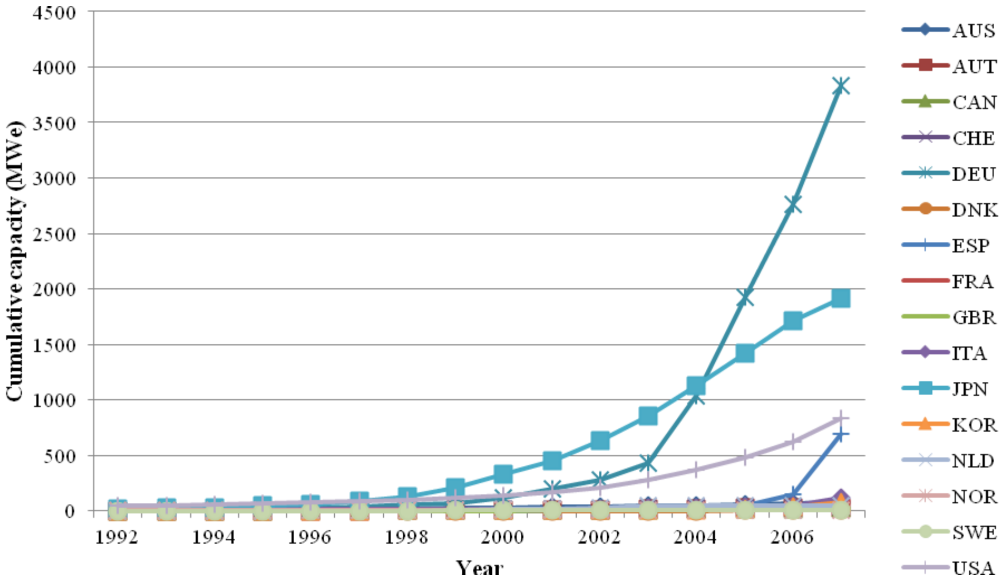
Note: AUT=Austria, CAN=Canada, CHE=Switzerland, DEU=Germany, DNK=Denmark, ESP=Spain, FIN=Finland, GBR=the United Kingdom, ITA=Italy, JPN=Japan, NLD=the Netherlands, NOR=Norway, SWE=Sweden, USA=the United States

Figure 3.5. Average investment cost of wind power, US$/kW (2000 prices)

For the last dependent variable ($CC_{i,n,t}$), I used cumulative (installed) capacity (megawatts electric, MWe) to represent technological diffusion. Recently, studies have increasingly focused on installed capacity, cumulative capacity, and cumulative production as measures of economies of scale, increased skill in the labor force, or technological diffusion (IEA, 2000; Junginger et al., 2005; Klaassen et al., 2005; Kobos et al., 2006; Söderholm and Klaassen, 2007). The data on cumulative capacity for solar

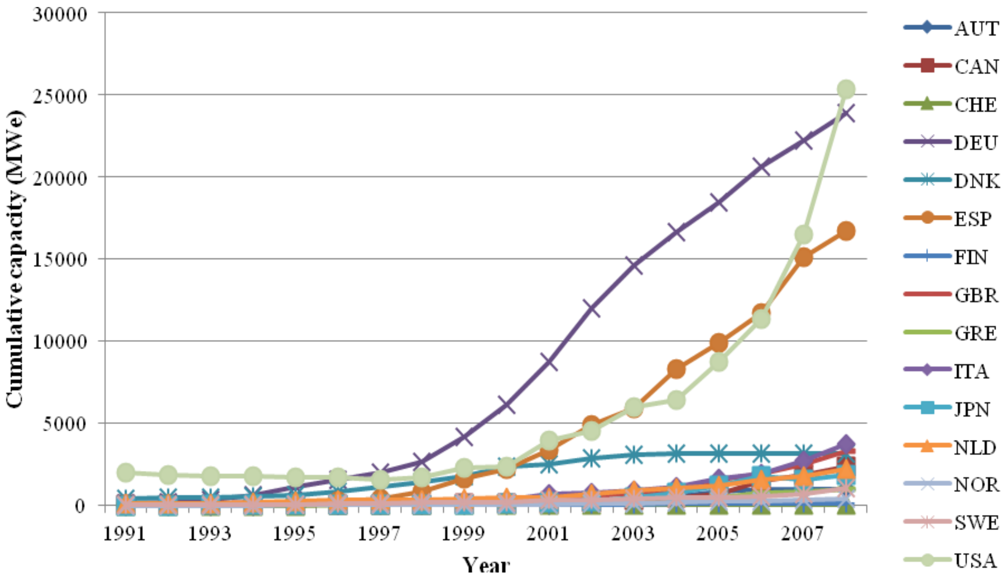
PV technology are available from volume 2008 of the series published by the IEA-PVPS (1992-2008) and the IEA (2009c), whereas those for wind power are available from volume 2008 of the series published by IEA (1998 – 2008) and the IEA (2009c).

Figs. 3.6 and 3.7 show the change of cumulative capacity for the analyzed countries over time. According to Fig. 3.6, most countries show increased cumulative capacity for solar PV, with Germany experiencing a jump since 2002, which is attributed to a large-scale PV demonstration program (i.e., 1000 Roofs Programme) and the FITs that support renewable electricity (IEA, 2004). Japan, as one of the largest manufacturers of PV cells in the world, has also seen a steep growth in capacity since 2000 due to the development of the domestic PV industry as well as considerable government R&D support. As shown in Fig. 3.7, Denmark, the United States, and Spain are the dominant drivers in increasing the global cumulative capacity in terms of wind power. Denmark and Spain have had notable expansions of both domestic and export markets through technological development of their wind turbines and the various support policies that ensure investors since 1990s (IEA, 2004). In the case of the United States, a federal tax credit for producers and introduction of RPS in particular states were significant in its fast-growing capacity since the late 1990s (IEA, 2004).



Note: AUS=Australia, AUT=Austria, CAN=Canada, CHE=Switzerland, DEU=Germany, DNK=Denmark, ESP=Spain, FRA=France, GBR=the United Kingdom, ITA=Italy, JPN=Japan, KOR=Korea, NLD=the Netherlands, NOR=Norway, SWE=Sweden, USA=the United States

Figure 3.6. Cumulative installed capacity of solar PV



Note: AUT=Austria, CAN=Canada, CHE=Switzerland, DEU=Germany, DNK=Denmark, ESP=Spain, FIN=Finland, GBR=the United Kingdom, ITA=Italy, JPN=Japan, NLD=the Netherlands, NOR=Norway, SWE=Sweden, USA=the United States

Figure 3.7. Cumulative installed capacity of wind power

3.4.2 Explanatory variables

Five types of renewable energy policies are presented in this study: public R&D as the instrument to support technological development ($TP_{i,n,t}$)[23] and public investments, tariff

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[23] The government support for R&D in time *t* affects contemporaneous invention but also can incorporate time lags on technology with certain characteristics, such as a technical standard, R&D efficiency, and path-dependence (i.e., technical inertia). We consider the variable of $TP_{i,n,t}$, which incorporates several time lags

incentives, renewables obligations, and environmental taxes as the instruments to promote use of renewable energy ($MP_{i,n,t}$). I regard the public R&D budget (Million US$, 2009 prices) as government support for R&D and invention by each technology as a continuous variable. The data were drawn from public research, development, and demonstration (RD&D) budgets disaggregated by type of technology in the *Energy Technology RD&D Budget 2010 edition* available through the IEA database (IEA, 2011c).

However, other policies are not continuous variables, and this study uses dummy variables to measure their effects. A dummy variable of a policy equals one if the policy is implemented or zero if the policy is not. Three reasons justify use of dummy variables for measuring market-pull policies. First, a dummy variable offers a strong point from which to compare effects of heterogeneous policies. As mentioned by Johnstone et al. (2010), policy adoption by country and technology are heterogeneous activities by nature, and therefore, are difficult to measure with a consistent criterion.

For example, renewables obligations vary according to the degree of legal force and the objective implemented. Furthermore, I aim to minimize the national variation for the goal and stringency in detailed programs of these policies. Second, I focus on the impact of policy introduction because I think it has a larger impact on the market than policy stringency (i.e., the goal and nature of a policy may have larger impacts on the renewable energy market than its stringency). Third, despite national variations, when considering a small change of stringency during the long-term implementation of policies, dummy

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from t-1 to t-3, as well as t created by renewable energy technology.

variables can be imposed in the model. For example, the United Kingdom has levied taxes with constant rates on fossil fuel from 2001 to 2005, and Germany has set small, increased, tariff incentives, 0.24€cents/kWh, from 1991 through 2000 (IEA, 2004). The data of these policies are taken from the IEA (2004) and the IEA/IRENA's on-line database (2011).

In the knowledge stocks, the domestic knowledge stock ($DKS_{i,n,t}$) and the overseas knowledge stock ($OKS_{i,n,t}$) are determined based on PCT applications. For the control variables, the ratio of total researchers per thousand persons in the labor force is used as the scientific resource ($SR_{n,t}$) per country; the data are taken from OECD (2010). In addition, the price of poly-silicon in solar PV technology (US$/kg) and the price of steel for wind power (US$/metric tonne) are imposed as raw material prices ($RMP_{i,t}$). Poly-silicon and steel are the dominant raw materials needed to build solar PV and wind power systems, respectively. I collected data on international prices because it is very difficult to collect the price data of two materials by country. The price of poly-silicon comes from global average export prices provided by the Korea International Trade Association (2009), and the price of steel comes from the global steel export price provided by World Steel Dynamic (2008).

I use the international price of coal (US$/tonne) as the price of fossil fuels ($FFP_{n,t}$) because it constitutes the largest share of raw material for electricity generation at 40.6% in 2009 (IEA, 2011b). These data, the total price of steam coal used in the national electricity sector, is drawn from the IEA (2009b). Lastly, the total amount of electricity generation ($TEG_{n,t}$) and GDP ($GDP_{n,t}$) are taken from electricity total gross production (GWh) IEA (2009a) and GDP data (US$, 2005 prices) as found in the OECD database (2011b). Tables 3.1 and 3.2 present the basic descriptive statistics for all variables used in the empirical analysis.

Table 3.1. Descriptive statistics for solar PV

Variable (Obs. 105)	Mean	Std. Dev.	Min.	Max.
Endogenous variables				
Patent proportion (%)	0.29	0.20	0.01	0.95
Cost (2000 US$/kW)	9418.19	4299.60	4150.54	26,385.79
Cumulative capacity (MWe)	217.62	576.58	1.50	3835.50
Exogenous variables				
Domestic knowledge stock (t)	45.84	75.22	0.52	451.29
Overseas knowledge stock (t)	634.41	442.71	44.03	1504.99
Domestic knowledge stock (t-1)	36.16	60.55	0.00	403.32
Overseas knowledge stock (t-1)	510.25	354.49	27.13	1191.06
Absorption capacity	0.65	1.34	2.89e-6	4.63
Policy variables				
Public R&D (t-1) (2009 million US$)	29.80	35.58	0.36	165.58
Tariff incentives	0.43	0.50	0	1
Renewables obligations	0.34	0.48	0	1
Environmental taxes	0.29	0.45	0	1
Public investment	0.32	0.47	0	1
Control variables				
Science resources	7.32	2.09	2.8	11.9
Raw material prices (US$/kg)	71.63	49.87	17.5	177
Coal prices (US$/tonne)	38.14	6.15	30.73	48.41

Electricity generation (GWh)	6.59e+5	8.98e+5	36,243	4.05e+6
Gross domestic production (2005 US$)	2.16e+6	2.46e+6	1.70e+5	1.15e+07

Table 3.2. Descriptive statistics for wind power

Variable (Obs. 62)	Mean	Std. Dev.	Min.	Max.
Endogenous variables				
Patent proportion (%)	0.34	0.48	0.00	2.35
Cost (2000 US$/kW)	1297.61	371.53	778.96	2622.10
Cumulative capacity (MWe)	2046.94	3238.42	5	18428
Exogenous variables				
Domestic knowledge stock (t)	20.42	24.80	0.95	125.26
Overseas knowledge stock (t)	216.56	136.91	38.93	451.06
Domestic knowledge stock (t-1)	16.79	22.50	0	123.04
Overseas knowledge stock (t-1)	179.90	123.95	37.57	429.48
Absorption capacity	0.38	0.56	0.00	2.05
Policy variables				
Public R&D (t) (2009 million US$)	12.03	15.08	0.13	63.57
Tariff incentives	0.37	0.49	0	1
Renewables obligations	0.39	0.49	0	1
Environmental taxes	0.42	0.50	0	1
Public investment	0.11	0.32	0	1
Control variables				
Science resources	7.12	2.64	2.7	13.4
Raw material prices (US$/metric tonne)	344.52	124.75	200	600
Coal prices (US$/tonne)	35.91	4.51	30.73	45.70
Electricity generation (GWh)	9.13e+5	1.40e+6	33969	4.30e+6
Gross domestic production (2005 US$)	2.83e+6	3.93e+6	1.04e+5	1.29e+07

3.4.3 Estimation method

For the empirical analysis, I needed to consider the endogeneity problem of the dependent variables: invention ($Z_{i,n,t}$), innovation ($SC_{i,n,t}$), and diffusion ($CC_{i,n,t}$). Because the dependent variable in an equation is included as an explanatory variable in another equation, a correlation between the variable and error term may characterize each equation. Therefore, due to this correlation, if I estimate the coefficients using ordinary least square (OLS) techniques, I may not obtain an unbiased estimation (Greene, 2011).

As solution to resolve the problem of endogeneity, it is worth considering two-stage least squares (2SLS) techniques using instrument variables because the fitted values by instrument variables are employed instead of the endogenous variables, and thus the correlation between independent variable and error term is removed. However, they are independent estimation techniques for individual equation referring to limited information, which ignore the correlation among equations and do not result in asymptotically efficient estimator. When considering that the fundamental reason to model simultaneous equations is to identify interactions and correlations among equations as well as variables, it is more appropriate to impose techniques to estimate not individual equation but the whole of equations simultaneously.

As the estimation method, therefore, I employ a three-stage least squares (3SLS) technique that considers not only the endogeneity but also the correlation among equations. All parameters of Eq.(3-6), (3-9), and (3-14) are simultaneously estimated by

3SLS techniques. In this study, the instrument variables used in 3SLS techniques are all exogenous explanatory variables except for endogenous variables (i.e., $Z_{i,n,t}$, $SC_{i,n,t}$, and $CC_{i,n,t}$). A static program used in this study is STATA.

3.5 Empirical Results

3.5.1 Estimation results: assessment of interrelations between the stages and static impact of policies

Tables 3.3, 3.4, and 3.5 show the estimation results of the parameters in the endogenous technological-change system. The results by different technologies are consistent with each other in terms of interrelation between the stages (i.e., the formation of a virtuous cycle), while some differences are found in the degree of policy impact.

Table 3.3 shows that the cumulative capacity is statistically significant for patent applications for both solar PV and wind power, suggesting that the more diffusions induced the more R&D activities and patent applications are realized through the positive effects of learning-by-using and market opportunity. The learning-by-using rates for solar PV and wind power are determined as 13.5% and 30.3%, respectively, which means that 13.5% of the proportion of patent applications in solar PV and 30.3% of the proportion of patent applications in wind power increase for each doubling of cumulative capacity. This implies that the more the renewable energy technologies diffuse, the more learning and knowledge from customers or stakeholders is undertaken, which broaden the scope of new ideas and facilitates inventions faster and easier.

The domestic knowledge stock is insignificant on invention, while knowledge spillovers from the overseas knowledge stock were found as significant factors that lead to increased domestic inventions (5% significant level). These findings suggest that the previous knowledge stock is regarded as an important factor in producing new ideas or knowledge by dynamic knowledge spillover, but the inventors have a strong tendency to absorb advanced knowledge and technologies from overseas rather than at home.

Table 3.3. Estimation results of the invention model

	Solar PV	Wind power
Endogenous variable		
Cumulative capacity	0.210***	0.521**
	(0.013)	(0.019)
Exogenous variables		
Domestic knowledge stock (t-1)	-0.048	-0.417
	(0.633)	(0.116)
Overseas knowledge stock (t-1)	0.221**	0.534**
	(0.037)	(0.013)
Policy variables		
Public R&D (t)		0.231*
		(0.088)
Public R&D (t-1)	0.164**	
	(0.048)	
Tariff incentives	0.376**	0.688**
	(0.019)	(0.013)
Renewables obligations	0.212	-0.763**
	(0.212)	(0.016)
Environmental taxes	0.136	0.006
	(0.477)	(0.981)
Public investment	-0.284**	-0.636*

	(0.017)	(0.096)
Control variables		
Science resources	-0.284	0.089
	(0.437)	(0.886)
Constant	-8.164***	-12.204***
	(0.000)	(0.000)
R^2	0.683	0.712
Learning-by-using rate	0.135	0.303

Note: The number in parentheses refers to a p-value and asterisks indicate statistical significance: * p<0.1, ** p<0.05, and *** p<0.01.

This surprising finding may be a result of the small number of leading countries dominating R&D activity for solar PV and wind power. According to the IEA (2008c), the top six countries (Japan, Germany, the United States, Italy, the Netherlands, and Switzerland) account for 72% of annual renewables R&D spending in the IEA countries during the 1990-2006 period. Also, in 2002, Japan, Germany, and the United States were dominant countries in terms of R&D budget allocations for solar PV, accounting for 70% of all spending, and three countries (Denmark, the Netherlands and the United States) have the largest part of the wind power R&D budget at 67% (IEA, 2011c). The advanced knowledge about these technologies is concentrated in a few leading countries, and solar PV and wind power are rapidly growing in the whole world, so some opportunities for worldwide transfer of the technology and knowledge may emerge.

From this analysis, I can say that in an environment of rapidly developing technology, diverse R&D strategies should be established because investing in R&D for developing absorption capability of overseas knowledge and utilizing it may be more efficient than accumulating domestic knowledge for technological change.

As a technology-push policy, the public R&D budget as a means to support technological development for increased knowledge of solar PV and wind power is significant at the 5% and 10% levels. From this result, one sees that direct effort of government for technical change of renewable energy has achieved substantial results. Although public R&D with respect to invention is inelastic (the values of both coefficients are smaller than 1), the public R&D elasticity is higher in wind power technology than in solar PV, which implies a higher public R&D-sensitivity for wind power.

This difference of elasticity between two technologies may depend on their technological maturity. According to the IEA (2006), as renewable energy technologies mature, more and more R&D activities are needed. That is, renewable energy technologies depend on geographic availability, and suitable areas are already taken by firms implementing a “low-hanging fruit” strategy, through which the options to accomplish the least internal costs are preferred. In addition, knowledge stock is not only obsolete but also accumulated less vigorously as time continues. Therefore, wind power, more mature technology, needs for more R&D activity, and the public R&D budget as government support can be useful in promoting R&D activity.

In market-pull policies, the tariff incentives appear to be the major driver of invention for both solar PV and wind power technology, which is consistent with some previous theoretical studies (Meyer, 2003; Lauber, 2004; Johnstone et al., 2010). As the tariff incentives provide a stable condition for technology and the market by guaranteed prices, investors spend in R&D to maximize profit, resulting in increased patent applications.

The renewables obligations show an insignificant effect on the invention of solar PV and even have a negative effect on wind power. This result may be explained by Meyer (2003): In a competition market system, renewables obligations not only create a number of uncertainties for investors but also create high transaction costs. In other words, renewables obligations induce electricity utilities to import cheaper technologies instead of investing in uncertain R&D. In this way, firms establish their short-term goal because renewable obligations are not distinguished by technology and are dependent on the bidding system.

The tariff incentives and renewables obligations appear to affect invention of both technologies similarly, showing a different result than that found by Johnstone et al. (2010), which emphasized a different impact of tariff incentives and renewables obligations by technology. Our result implies that to engender fundamental changes in rapidly growing technology the policies that encourage stable prices and markets are more effective than policies that lead to market competition.

Public investment reduces knowledge generation because it is characterized by subsidies for installation or market expansion of renewable energy, and therefore firms may have less incentive to develop their technologies. This result implies that even though the public investment is useful for an initial expansion of the market, it may not work in the long-term progress of technology. I found no evidence for a direct effect of environmental taxes on invention.

Table 3.4 presents estimations of the parameters on the innovation (cost) model. Regarding the impact of cumulative capacity, results of both technologies, as expected, carry negative signs. They show statistical significance for system cost reduction, supporting the hypothesis that cost reduction occurs by learning-by-doing effects if production of components accumulates or diffusion of technology increases. The estimated learning-by-doing rates of solar PV and wind power are 12.9% and 6.1% respectively; the values range between 4% and 25% in previous studies[8] about experience curves.

Table 3.4. Estimation results of the innovation model

	Solar PV	Wind power
Endogenous variable		
Cumulative capacity	-0.199***	-0.091**
	(0.000)	(0.011)
Exogenous variables		
Domestic knowledge stock (t)	-0.103***	-0.089*
	(0.001)	(0.098)
Overseas knowledge stock (t)	0.002	-0.023
	(0.937)	(0.592)
Absorption capacity	-0.015	0.088
	(0.509)	(0.410)

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[8] See Junginger et al.(2005) for more detail information about various learning rates.

Policy variables		
Tariff incentives	0.072	-0.056
	(0.241)	(0.373)
Renewables obligations	-0.132**	0.043
	(0.035)	(0.530)
Environmental taxes	-0.116*	-0.219***
	(0.091)	(0.001)
Public investment	-0.229***	0.262***
	(0.000)	(0.002)
Control variables		
Raw material prices	0.135***	0.328***
	(0.000)	(0.000)
Gross domestic product	0.353***	0.094
	(0.000)	(0.222)
Constant	4.771***	4.731***
	(0.000)	(0.000)
R^2	0.801	0.770
Learning-by-doing rate	0.129	0.061
Learning-by-searching rate	0.069	0.060

Note: The number in parentheses refers to a p-value and asterisks indicate statistical significance: * $p<0.1$, ** $p<0.05$, and *** $p<0.01$.

Meanwhile, the accumulation of domestic invention (domestic knowledge stock) leads to innovation and encourages additional learning-by-searching effects, suggesting that the movement from basic research to optimal design is improved by accumulation and gradual organization of domestic knowledge. The estimated learning-by-searching rate from domestic knowledge stock in solar PV and wind power is 6.9% and 6.0%

respectively. Although the learning-by-doing rate and learning-by-searching rate could differ by region, time period, and depreciation rate for analysis, our results are in line with those from previous research (Kouvaritakis et al., 2000; Miketa and Schrattenholzer, 2004; Kobos et al., 2006).

From this result, I offer empirical evidence that diffusion of renewable technologies through market expansion lowers the system cost (i.e., innovation) via two learning effects: learning-by-doing on through the production channel and learning-by-using through the R&D channel.

However, I cannot find any direct learning effects from overseas knowledge; the result shows insignificant levels of impact for both overseas knowledge stock and absorption capacity. When considering this finding with the invention result, I can see that overseas knowledge does not affect domestic innovation (cost reduction) directly but has an indirect impact on domestic innovation by increasing knowledge generation due to dynamic spillover. This result is similar to that of Popp (2006), whose work emphasized that overseas technology and knowledge transfer to domestic innovation is indirect. It implies that overseas knowledge adapted by R&D to domestic market conditions as well as knowledge-transfer promotion policies are important to accomplish innovation.

In both solar PV and wind technologies, the tariff incentives are insignificant on system cost and stand in contrast to their positive impacts on knowledge-generation in the invention model. The renewables obligations and environmental taxes are useful instruments to reduce system costs of solar PV, showing significance at the 5% and 10%

levels, respectively. Both renewables obligations and environmental taxes remain unvaried by technology type, and therefore, they can induce a competitive market to employ the cheapest options. While solar PV creates the highest cost for electricity generation among renewable energy technologies (IEA, 2003), I can infer that quantity-based and environmental policies that lead market competition encourage cost reduction in technologies with a high potential for cost reduction.

Wind power showed declining costs only through environmental taxes. This finding means that renewables obligations may not exert a significant impact on additional reductions of cost for wind power because of its comparative advancement in terms of price competitiveness among renewable energy technologies. However the environmental taxes make electricity utilities consider multiple clean technologies, including nuclear, carbon capture and storage (CCS) technology, and integrated gasification combined cycles, as well as renewable energy technologies. Therefore, environmental taxes provide motivation to reduce costs for wind power developers who face relatively high cost compared to developers of other clean technologies.

As a result, I found that competition-leading instruments (i.e., quantity-based and environmental policies) to achieve renewable energy expansion are more efficient in driving costs down than is a price-based policy. However they may put greater pressure on developers to acquire the best available location, and due to a number of uncertainties and high transaction costs, they push producers toward short-term import of cheap foreign equipment rather than invention by R&D. Our empirical results coincide with previous literature exploring these theories (Mitchell, 2000; Ibenholt , 2002; Menanteau et al., 2003; Lauber, 2004; Söderholm and Klaassen, 2007).

The raw material price of each technology is in proportion to each system cost, illustrating that raw materials play a large part in the cost. Also GDP as representing development of infrastructure shows unexpected results in solar PV, but is an insignificant factor on wind power.

Lastly, from the diffusion model, one can preferentially identify a simultaneous relationship between innovation and diffusion as decreased system costs have significant (at the 1% level) impacts on diffusion of both technologies. The impact of declined system costs acts as the most dominant factor for escalating use of a technology, implying that expansion of the renewable energy market responds to the cost of technology, just as in the market of general goods. This result supports the last step of the virtuous cycle, and from Tables 3.3 to 3.5 I can identify that a virtuous cycle is built upon solar PV and wind power technology.

Although a lively argument about major instruments to promote diffusion of renewable energy technology is in progress, our results about static impacts of policies on diffusion are mixed. The tariff incentives are major drivers to diffuse solar PV technology, while the renewables obligations and public investment are significant on diffusion of wind power when the endogenous factor (i.e., system cost) and other factors that affect diffusion are controlled.

Table 3.5. Estimation results of the diffusion model

	Solar PV	Wind power
Endogenous variable		
System cost	-3.826***	-4.376***
	(0.000)	(0.000)
Policy variables		
Tariff incentives	0.566**	0.173
	(0.022)	(0.548)
Renewables obligations	-0.511	0.594*
	(0.105)	(0.050)
Environmental taxes	-0.761**	-0.768**
	(0.023)	(0.028)
Public investment	-0.999***	0.842**
	(0.000)	(0.018)
Control variables		
Fossil fuel prices	1.968***	5.024***
	(0.001)	(0.000)
Electricity generation	1.376***	0.176
	(0.000)	(0.300)
Constant	14.077***	17.179***
	(0.002)	(0.000)
R^2	0.786	0.858

Note: The number in parentheses refers to a p-value and asterisks indicate statistical significance: * p<0.1, ** p<0.05, and *** p<0.01.

In the case of solar PV, tariff incentives appear to be effective because they provide a stable and safe floor for the price in the early stage of technical development and comparative high cost, which enables solar PV technology potential for an expanding market. Meanwhile, the renewables obligations have a positive impact on increased diffusion of wind power, but it has an insignificant impact on solar PV, with a comparatively high cost, because competition-leading instruments are more effective on diffusion of technology which has a competitive advantage in terms of price. The environmental taxes exert a negative impact on solar PV and wind power diffusion because electricity utilities employ other technologies with lower costs, whereas public investment shows mixed results.

The previous literature suggests that both policies have helped renewable energy technologies to diffuse widely, and comparing their efficiency in terms of diffusion is difficult due to national variations of introduction and performance of policy (Menanteau et al., 2003; Lauber, 2004; Söderholm and Klaassen, 2007). Nevertheless, when considering a policy’s efficiency by technology maturity, our results are consistent with Lauber (2004), who indicated that FIT can be helpful in market creation of technology in the early stage, while RPS is more appropriate for technology with advanced market competitiveness.

The price of fossil fuels is identified as one of the most dominant factors in the increased use of renewable energy, suggesting that as the price of fossil fuels increases due to its exhaustion as a natural resource, diffusion of renewable energy technologies will increase. In terms of total electricity generation, our results are significant only for solar PV technology.

Although a part of the results is consistent with previous studies and the other part is not, I suggest the existence of a virtuous cycle of learning effects among invention, innovation, and diffusion of renewable energy technologies. In other words, market-pull policies create an initial market to introduce renewable technology, and technology-push policies allow producers to overcome technological barriers more easily. Then, diffusion of renewable technologies through market expansion induces a contemporaneous decrease in the system cost (i.e., innovation) of renewable energy by learning-by-doing and an increase in knowledge-generation (i.e., invention) by learning-by-using. This situation results in greater accumulation of organized knowledge stock and lowers the cost by more learning-by-searching activity. The innovation (i.e., cost reduction) by these learning effects leads to increased diffusion of technologies by enhancing the price competitiveness while reducing technical uncertainty. As a result, a virtuous cycle, diffusion – increased invention – innovation (cost reduction) – diffusion is created and policies promote this virtuous cycle.

3.5.2 Simulation results: The virtuous cycle and dynamic impacts of policies

In the previous section, I show the determination of the static impact of policies on each stage. In the long-term, the static impact can be amplified by the learning effects associated with policy, and I regard this circulated impact a dynamic aspect of the change of the renewable energy system. To avoid underestimating the effect of policies, the dynamic impact is important to assess.

For example, in the case of solar PV, tariff incentives have a static impact on the invention and diffusion stages. In the long- term, this circulation of tariff incentives recurs by a virtuous cycle and their static impact can be amplified by learning effects with decreasing return. As a result, the dynamic impact of tariff incentives on the invention stage can be calculated as their static impact plus the accumulated effect of learning-by-using. In addition, although tariff incentives do not statically affect the innovation stage, dynamic impacts of tariff incentives on the innovation stage emerge by the accumulated effects of learning-by-searching and learning-by-doing as initiated by tariff incentives.

Tables 3.6 and 3.7 describe the simulation results for dynamic policy impacts on solar PV and wind power, respectively. For comparison, each table also shows static impacts described in Tables 3.3, 3.4, and 3.5. As shown in Tables 3.6 and 3.7, long-term, dynamic impacts have converged values due to the decreasing returns of the learning effects (i.e., the numerical values of learning effects are less than one unit). In both solar PV and wind power technology, the static impacts of various policies are amplified by learning effects, and one can also find dynamic effects undiscovered in the estimation results for determining static impacts.

Table 3.6. Simulation results for estimating the dynamic effect of the policies on solar PV technology

Policy	Invention		Innovation (Cost)		Diffusion	
	Static	Dynamic	Static	Dynamic	Static	Dynamic
Technology-push policy						
Public R&D	0.164	0.251	N.A	-0.108	N.A	0.414
Market-pull policies						
Tariff incentives	0.376	1.337	-	-1.049	0.566	4.579
Renewables obligations	-	0.680	-0.132	-0.846	-	3.237
Environmental taxes	-	-0.427	-0.116	0.333	-0.761	-2.034
Public investment	-0.284	-0.600	-0.229	0.132	-0.999	-1.506

Note: ‘-’ indicates an insignificant impact.

Table 3.7. Simulation results for estimating the dynamic effect of the policies on wind power technology

Policy	Invention		Innovation (Cost)		Diffusion	
	Static	Dynamic	Static	Dynamic	Static	Dynamic
Technology-push policy						
Public R&D	0.231	0.349	N.A	-0.052	N.A	0.226
Market-pull policies						
Tariff incentives	0.688	1.038	-	-0.154	-	0.672

Renewables obligations	-0.763	-0.375	-	-0.034	0.594	0.744
Environmental taxes	-	0.249	-0.219	-0.285	-0.768	0.477
Public investment	-0.636	-1.357	0.262	0.509	0.842	-1.384

Note: '-' indicates an insignificant impact.

According to the result of public R&D, the technology-push policy not only encourages knowledge-generation directly, but also positively affects cost reduction through learning-by-searching. Furthermore, this reduced cost increases technology diffusion.[24] When considering its inducement of international knowledge spillover, the technology-push policy can be regarded as a key force in driving fundamental change of technology.

I focus on the comparison between dynamic impacts of price-based and quantity-based policies because the two have been treated as representative renewable energy policies in harmonization (Lauber, 2004). As shown in Figs. 8 and 9, in terms of long-term dynamic impacts, tariff incentives throughout the technological change system outperform renewables obligations in both technologies. Although tariff incentives do not exert direct effects on the innovation stage, intense promotion of knowledge-generation and development of new technology by tariff incentives induce large cost reduction and

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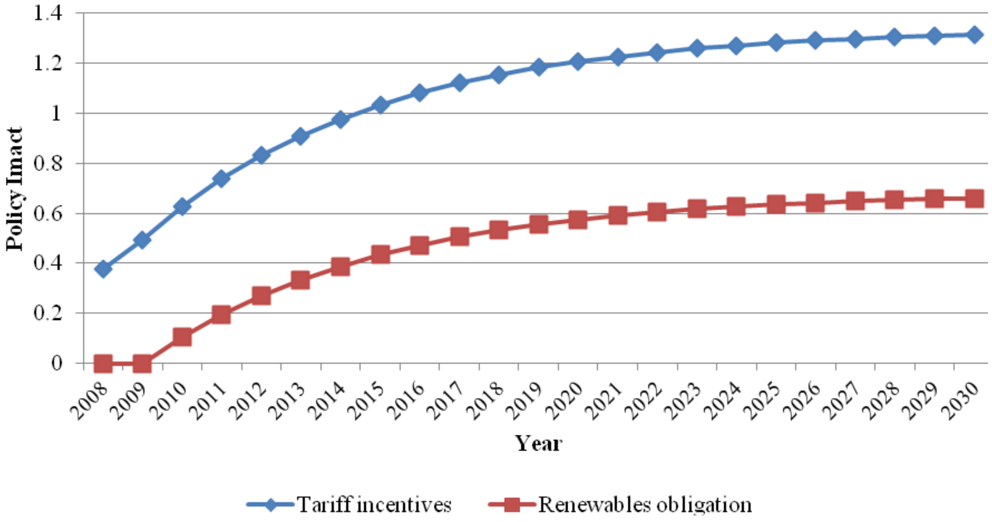
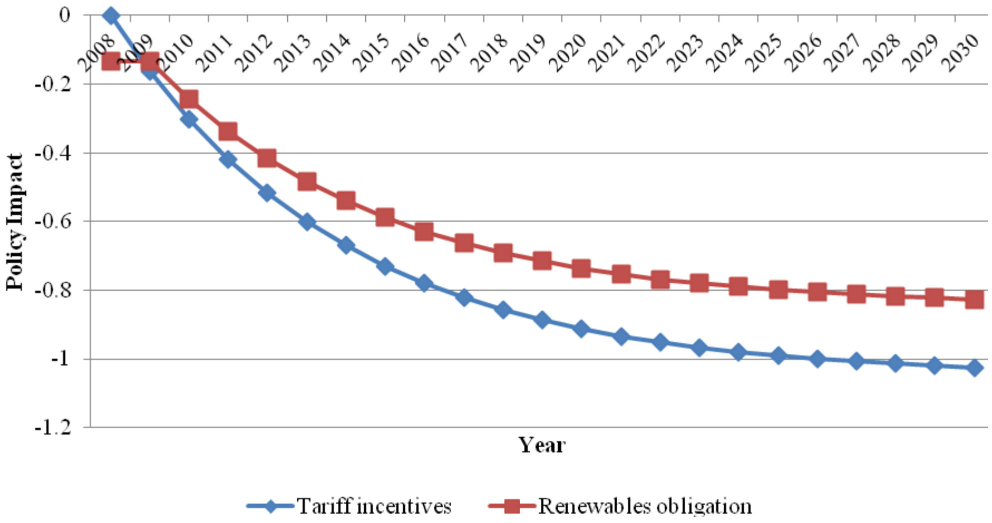
[24] To determine whether the public R&D reflects an overinvestment on innovation of renewables technologies or not, we calculated public R&D efficiency with respect to cost reduction (the ratio of total cost reduction, which reflects amount of diffusion increased by public R&D, to the input of the public R&D budget) based on our dynamic impact results of public R&D using cross-country average data in the analysis periods for each technology. The calculation shows the ratio of solar PV and wind power as 227.87 and 228.89, respectively, implying that public R&D do not reflect an overinvestment and shows substantial efficiency for innovation (cost reduction).

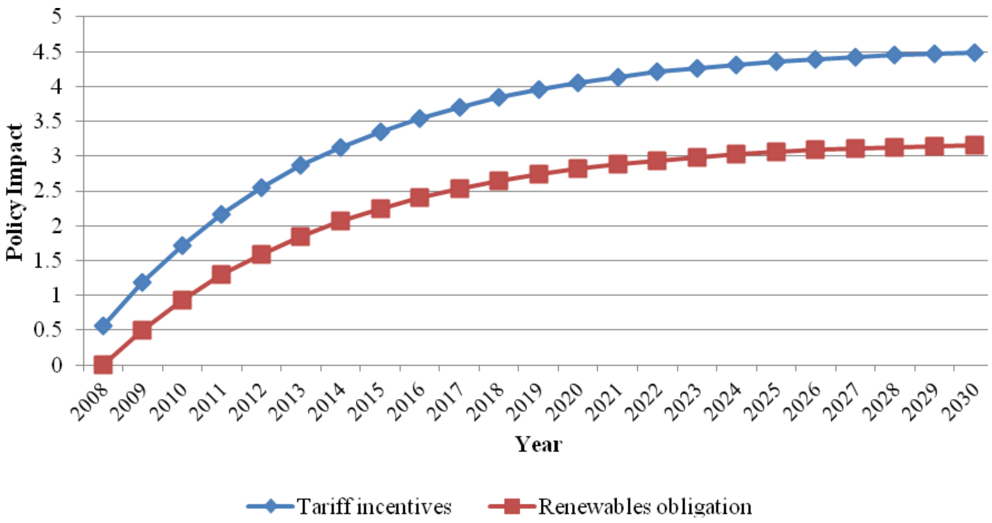
diffusion, surpassing those of renewables obligations in the long-term. Renewables obligations show more market efficiency than tariff incentives, but it discourages renewable producers to invest in R&D activity due to high pressures to reduce costs, weakening the long-term innovation engine.



(a) Invention

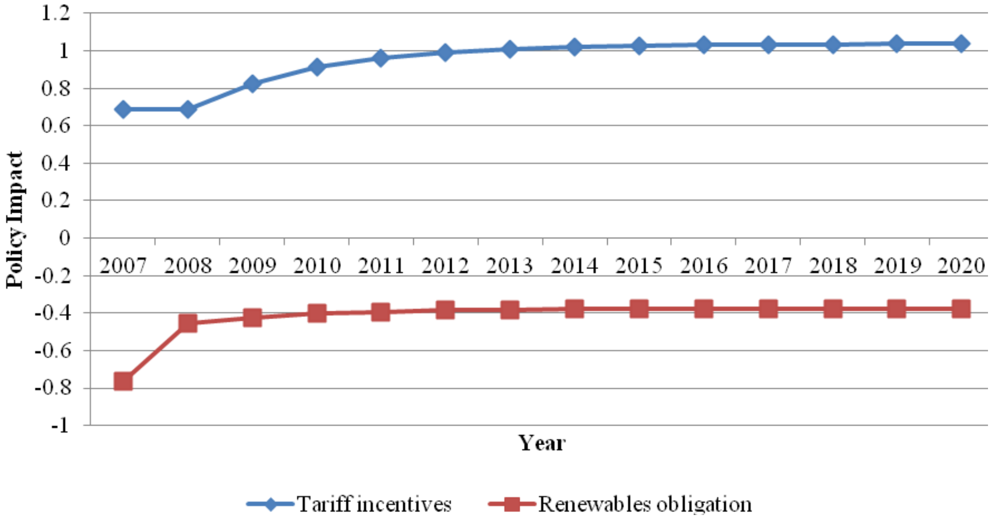


(b) Innovation (cost)

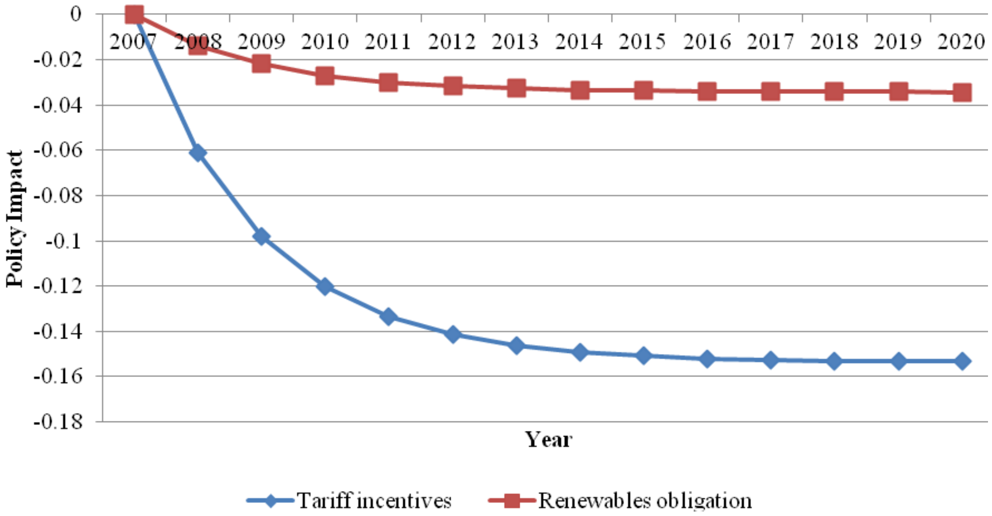


(c) Diffusion

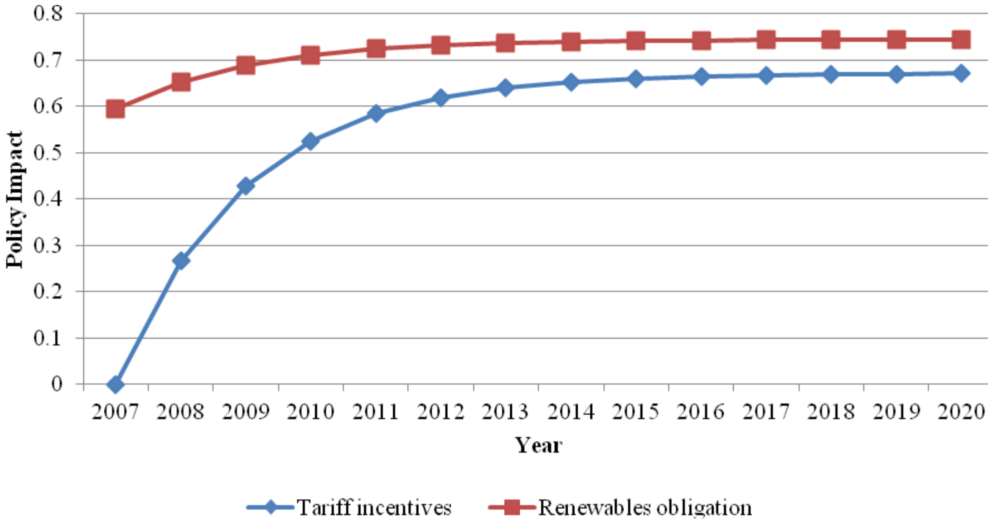
Figure 3.8 Dynamic impact of tariff incentives and renewables obligations on (a) invention, (b) innovation, and (c) diffusion of solar PV technology



(a) Invention



(b) Innovation



(c) Diffusion

Figure 3.9 Dynamic impact of tariff incentives and renewables obligations on (a) invention, (b) innovation, and (c) diffusion of wind power technology

A significant difference between two technologies is seen from the impact of environmental policy, which is negative on solar PV but positive on wind power. Although the static impact of environmental taxes is significant on cost reduction in both technologies, it has a larger impact on wind power (-0.219) than on solar PV (-0.116), which may mean that environmental taxes had enough positive impact on wind power to countervail the negative impact of them on the diffusion stage. This result implies that environmental policy is useful for long-term innovation and diffusion of wind power technology, which has a comparatively high price competitiveness and follows the argument of Foxon et al. (2005), who suggested that the more mature the renewable energy technology, the more appropriate it is for innovation and market penetration when not directly supported but acting in a competition system that includes environmental tax or trading schemes.

Meanwhile, public investment imposes a negative effect on the technological change system. Through this result, I confirm that public investment, as made via a simple fiscal subsidy, does not give equipment developers motivation for development of new technology nor does it intensify their pressure on cost reduction because it is not market-based but government controlled. Therefore, even though public investment induces initial expansion of renewable energy and plays a significant role in popularizing technologies at the demonstration stage, it may hamper technological progress under a virtuous cycle time due to its negative effect on motivation for innovation.

3.6 Conclusions

Recently, harmonization of renewable energy policies is gaining attention as an important and critical issue. To find an appropriate means of invoking policy for renewable energy, I assessed performance of renewable energy-related policies over the entire technological-change system from invention to diffusion. Specifically, I determined impacts of policies on the endogenous technological-change system that is disaggregated into invention, innovation, and diffusion stages.

As a result, I confirm that interrelations between invention, innovation, and diffusion create a virtuous cycle in both technologies. In assessment of policies, above all, I estimated the static impact of renewable energy-related policies, under control of these interactions, in a technological change system and show that although targets of policies are similar in promoting renewable energy deployment, the policies that exert direct influence at each stage differ. In addition, by estimating the dynamic impacts of the policies on the system, I try to find long-term solutions for sustainable development of renewable energy technologies.

The three key findings are following as: First, the technology-push policy (i.e., public R&D) is useful in knowledge generation of both technologies, which implies that direct efforts of the government for knowledge generation and new technology are a fundamental driving force for long-term technological change. In dynamics of its impact, the technology-push policy not only encourages knowledge generation directly, but also exerts positive impacts on cost reduction through learning-by-searching, and furthermore, it is a significant factor on diffusion.

When considering knowledge spillover, the technology-push policy grows in importance. An external factor on the technological change system, overseas knowledge spillover, far from affecting domestic innovation directly, influences positive impacts on domestic R&D activity (i.e., invention), and as a result, it exerts an indirect impact on domestic innovation by increasing knowledge generation. This finding suggests that domestic R&D efforts, including public R&D, are necessary for adaptation of overseas knowledge to domestic market conditions as well as for domestic sources of invention. In addition, an efficient strategy to transfer the advanced technology and new knowledge from overseas to domestic R&D, such as advanced patent system, encouragement of foreign direct investment (FDI), and international cooperation for technology development, is needed.

Second, although renewable energy-related policies focus on promoting use and deployment of renewable energy, their static effects can differ throughout the technological change system, and in the long-term technological change, the price-based policy is more effective on invention, innovation, and diffusion than the quantity-based policy due to its inducement of dramatic technological change. This result implies that price-based policies, along with a technology-push policy, can be regarded as a long-term sustainable solution for development of technology as well as installation, and therefore policy makers should consider them an important requirement in the harmonization of support schemes.

Third, if the renewable energy technology matures more and more, it is necessary to impose policy instruments that induce competition between renewable energy technologies and the broader and the more advanced technologies out of them. The quantity-based and environmental policies, of course, are significant to long-term technological change as they feature more efficient cost reduction, but I suggest a different implication, based on technology maturity, in terms of instrument adoption. In the early developing stages, a quantity-based policy, which includes renewables obligations that induce competition in renewable energy markets, is efficient for long-term technological change. However, on the middle- and late-developing stages, environmental policy that induces competition in the entire energy market, in addition to a quantity-based policy, can promote long-term technological change.

Although this study shows remarkable and interesting results, several limitations need resolving and further works undertaken in econometric estimation. First, dummy variables used to represent market-pull policies precluded us from measuring impacts by policy stringency. Second, I indicated that the limitation of fixed country-specific effect is assumed despite variation in national situations. Third, I assumed fixed depreciation and diffusion rates for modeling knowledge stock although they may be varied by time flow and characteristics of technology. In the future, researchers can draw more lessons, with more sophisticated models and data, as they apply our endogenous technological-change system, as based on learning effects, to another industry sector.

Chapter 4. The Role of Innovation and Policies for Sustainable Growth of Renewable energy Technology

4.1 Introduction

Currently, the global market of renewable energy is not only scaling up but also changing more and more toward an open-door system, because the initial goal in the supply of renewable energy focused on solving the global environmental problem and only recently did the governments of all countries encourage the adoption of renewable energy to improve their energy security and accomplish sustainable economic growth (IEA, 2011c). A noticeable economic value of renewable energy, beyond the environmental solution, is that it induces increased market potentials and makes a country introduce open markets with international trade for a more efficient transaction of goods and technologies.

In addition, the global market of renewable energy has been growing stably from strengthened global regulations, such as the Climate Change Convention, and massive investments by countries (see Annex I) in renewable energy installation. Presently, the renewable energy industry is showing further consolidation and, at the same time, becoming more competitive as the developing countries enter the market. For example, China plays a key role in driving the manufacturing of renewable technologies, particularly wind power, solar PV, and solar hot water systems (REN21, 2010).

Furthermore, the R&D efforts to develop new and advanced technologies with government support have induced the increased interest of electricity utilities and have declined the costs of renewable technologies. In public R&D investment, despite national variation, the ratio of renewable energy technology to total energy R&D is stable, averaging 7.6% until 2006, and increasing only recently; for instance, in the United States, it's the share of investment in R&D increased to more than 10% (IEA, 2006; IEA, 2011b). The compounded annual growth rate (CAGR) of the government's R&D also shows the increased investment in renewable energy as 29% during the period 2004–2010 (UNEP and Bloomberg New Energy Finance, 2011).

As discussed in Chapter 3, these market-pull and technology-push investments in new technology development will enable the evolvement of an early domestic market. Furthermore, such domestic innovations and renewable energy policies will affect the advancement of renewable energy technologies in foreign competitiveness, because the firms will aim to enter the global market as well as the domestic market. Therefore, it is important to identify not only the domestic diffusion of renewable energy technologies but also foreign trade competitiveness.

The foreign trade competitiveness of a country can be observed from its international trade flows from/to the world, including its export and import activities; domestic R&D activity, technological diffusion, and government policies can have direct and indirect interrelations with these trade flows. R&D plays a significant role as the start point for domestic innovation and technological diffusion, and also plays an intermediate role of connector between international trade and domestic innovation. In other words, the increased absorption of foreign technology through imports may complement or substitute R&D activity, while increased exports may promote R&D for the same reason for domestic market expansion.

Domestic technological diffusion increases the market size for renewable energy, which induces increases in market competition through more firms entering the market. As the market continues to expand, the resulting increase in domestic demand will lead to larger import flows, and the increase in supply will have a positive effect on export flows. Further price competitions may also affect foreign trade activities, for example, the import of cheaper facilities or components or advanced technologies and the export of more competitive goods.

In addition, it is important to identify the effects of the renewable energy policies on international trade, because renewable energy policies that induce domestic technological diffusion can affect the export and import performance of countries through R&D and market expansion indirectly. This analysis of policy impacts on international trade will enable policy makers to formulate plans and strategies for increasing foreign competitiveness.

The objective of this chapter is to construct a sustainable growth model of renewable energy technology reflecting trade activities for higher foreign competitiveness as well as domestic innovation systems. The chapter also determines the role of renewable energy policies on each stage and over the system. Specifically, I expand the domestic innovation system constructed in the previous chapter with international trade activities, which enables identification of interrelations between domestic innovation systems and international trade. To establish the interrelations between domestic and foreign activity systems, I consider domestic technological diffusion (or market expansion) as well as R&D activities as endogenous factors affecting foreign trade. This study also expands upon Lim’s (2011) study, which estimated the interrelation between R&D and exports, and establishes a more refined model that can provide more implications. Similarly, solar PV and wind power technologies used to generate electricity are considered and estimated using an unbalanced panel dataset consisting of 16 countries for solar PV and 14 countries for wind power from 1991 to 2008.

The rest of this chapter proceeds as follows. Section 4.2 determines the background theories, and Section 4.3 builds the empirical model. Section 4.4 describes data used in this study. Section 4.5 presents results and discussions. Section 4.6 concludes this study.

4.2 Theoretical Background

4.2.1 R&D activity and international trade

From a theoretical perspective, firms invest in R&D activity to explore future productivity or new technology, resulting in increased profits from exporting (Aw et al., 2008). Several empirical studies in the literature have identified the relation between firm-level productivity, ownership, characteristics, and export decisions (Trefler, 2004; Verhoogen, 2008). These studies support the strong evidence that more productivity causes firms to decide to enter the export market (Aw et al., 2008). In recent years, many studies have regarded R&D activity as productivity enhancement and tried to determine the linkage between investment in innovations and the decision to export—specifically the feedback including learning-by-exporting from export to firm's R&D (Delgado et al., 2002; Topalova, 2004; De Loecker, 2006).

Proceeding further from the linkage between R&D and trade, some studies have suggested that R&D activities promoted by the new markets might lead to increased trade. Zhao and Li (1997) analyzed the impact of investment in R&D in the Chinese manufacturing industry on their propensity to export. They show that an increase in innovations through R&D enables firms to decide on exporting and leads to increases in export volumes of the related industry. Greaker (2006) claims that the new market created will induce an increase in the firms' market access, and, as a result, the firms' R&D, by inducing more competition in the market, will have a positive influence on exports.

Tan and Hwang (2002) determine the impact of technology inflows through imports on in-house firm-level R&D. They show that the relationship between imported technology and in-house R&D is complementary, but technology inflows might induce higher R&D expenditure to adapt foreign technology to domestic conditions. Recently, Lim (2011) determined the relationship between R&D and export in the renewable energy industry. He finds that knowledge accumulation through increased R&D has a major positive effect on exports.

4.2.2 Renewable energy policy and international trade

The Poter hypothesis, resulting from one of the various discussions on the relationship between trade flows and government policies, argues that the export of energy technologies depends on the stringency of environmental regulations, and results from the regulations' pressure on the firms. Firms engage in innovations to satisfy the regulations and, furthermore, improve their dynamic competitiveness (Poter and van der Linde, 1995).

The following studies substantiate the above hypothesis. Greaker (2006) analyzed the impact of policy regulations on exports by simulating the price, demand, and supply functions and found that highly stringent policies have a positive effect on increasing exports. Constantini and Crespi (2008) also provide evidence supporting the Poter hypothesis, estimating the effect of environmental regulations on export flows using a gravity model. They emphasize that strengthening environmental regulations is a crucial driver for enhancing export performance.

With regard to renewable energy policies, Rickerson et al. (2007) insist that RPS is effective to meet the goal of domestic diffusion in renewable energy but is negative for trade performance, because the competitive market formed by RPS will pressurize the firms to reduce costs, and therefore the firms will prefer to import equipment rather than develop them. Carbon taxes would work against energy-intensive industries, which their impact, depending on the position of bilateral trade (World Bank, 2009; Zhao, 2010). According to Zhao (2010), in bilateral trade, carbon taxes levied only on exporting countries will have little impact on both countries (i.e., the exporting and importing countries), but carbon taxes levied only on the importing countries will have a negative effect on the exporting countries. In addition, from statistical estimation, the effect of carbon taxes on the home country appears to be negative on export performance.

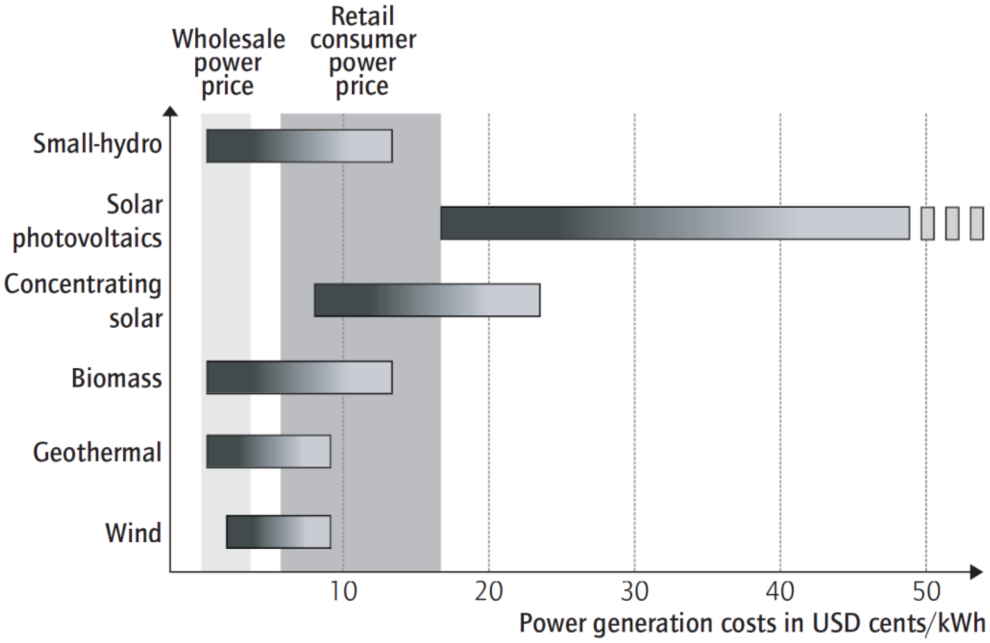
In contrast, Lim (2011) analyzes the relationship between renewable energy policies and export flows for solar PV and wind power, and finds that both RPS and environmental taxes play a significant role in increasing exports. He explains this as the positive effects emerging from the market, which expanded through those policies.

However, these studies have not taken into account the interactions between R&D activity and trade, including exports and imports, and therefore, do not provide the policy impacts on R&D and trade performance, excluding mutual endogeneity. In addition, not many empirical studies have been made on clean energy technology, because the clean energy industry has risen only recently.

This study evaluates how the policies interrelate in R&D activity and international trade for renewable energy technology, that is, solar PV and wind power. I determine the interactions between R&D, imports, and exports in the renewable energy industry by constructing simultaneous equations and thereby explain whether there is a complementary or a substitute relationship between R&D, imports, and exports. This analysis will provide significant implications for policy makers to understand which policy is effective for imports and exports and create a long-term efficient strategy for sustainable economic growth.

4.2.3 Different technological maturity and cost competitiveness in renewables technology

Although it is difficult to measure the level of technological advancements clearly due to heterogeneity of the systems and different technology-driven approaches, previous studies have considered various criteria to evaluate the level of technological and market development. First, the representative criterion is cost or price competitiveness. As shown in Fig. 4.1, based on OECD and IEA (2003), renewable energy technologies can differ by generation cost competitiveness, and solar PV technology has high costs while wind power has low costs. The report emphasizes that tone should consider cost competitiveness by technology when establishing the support policies for renewable energy. Johnstone et al. (2010) find a different policy effect on R&D by renewable energy technology, and suggest that this difference by technology can be attributed to the relative cost competitiveness, which largely affects the utilities' choice to adopt renewable energy technologies. This cost competitiveness is considered efficient information, because it reflects both the market condition as well as technological development. Therefore, it is appropriate to determine the technological advancement of renewable energy technology on the basis of the relative cost competitiveness.



Source: OECD and IEA, 2003

Figure 4.1 Cost competitiveness of renewable energy technology

Second, in terms of a roadmap for technological development, wind power technology should concentrate on cost-efficiency by increasing the wind turbine diameter and tower height (IEA, 2009e), while solar PV should develop new-generation technology, for example, from crystalline silicon(c-Si)-type PV cells to thin film-type PV cells, with new material and fabrication (IEA, 2008d). A major difference between the two technological roadmaps is that the former enhances cost competitiveness by improving equipment structure using existing technology, whereas the latter concentrates on improving the material and processes based on latest technology.

Third, with regard to market penetration, wind power, adopted since the 1970s, has the largest proportion in renewable energy technologies' deployment excluding small-hydro power; based on proven technology, wind power is in the early stage of development, and has relatively high cost competitiveness (OECD and IEA, 2003; Foxon et al., 2005; IEA, 2011e). In the early stage, the European countries including Denmark, Spain, and Germany were dominant, but in recent times, the developing countries such as China and India are penetrating the market, making the market more competitive. Solar PV technology has been diffusing since the middle of the 1990s, and is showing rapid growth (IEA, 2008d). However, solar PV is in the developing stage, and is passing through the pre-commercial stage, and still has low cost competitiveness, despite the improved efficiency of solar PV conversion (OECD and IEA, 2003; IEA, 2008c; IEA, 2008d).

In sum, wind power has passed through various learning and technological development phases through its continuous and widening spread, and as a result, its cost competitiveness has been enhanced. However, despite a more competitive market, wind power does not enjoy much potential for higher cost competitiveness through technological development owing to the principle of *low-hanging fruit*, but rather may have more potential through market transactions in international trade. On the other hand, solar PV, in its early developing stage, has relatively more potential to develop technology and enjoy market opportunities, which require new technologies to enhance energy-conversion and cost-effectiveness. Therefore, with regard to solar PV, more investment in R&D may be an efficient strategy to achieve higher cost competitiveness.

4.3 Empirical Model

This thesis builds a sustainable growth model, expanding the domestic innovation system with international trade activities. This model builds interrelations between the domestic and foreign activity systems, considering domestic technological diffusion (or market expansion) as well as R&D as endogenous factors. Therefore, an R&D model (i.e., invention model) is introduced, which acts as the link between domestic innovation and foreign activities. In addition, this thesis builds an export and import model that affects endogenous domestic R&D and technological diffusion.

4.3.1 R&D model: knowledge generation through international trade and spillover

To determine interrelations between domestic R&D and international trade, this study establishes a R&D model that functions similarly to the invention model in Chapter 3, but introduces endogenous variables in terms of export and import as follows:

$$\begin{aligned}\ln Z_{i,n,t} = {} & a_0 + a_1 \ln CC_{i,n,t} + a_2 \ln EXP_{i,n,t} + a_3 \ln IMP_{i,n,t} + a_4 \ln DKS_{i,n,t-1} \\ & + a_5 \ln OKS_{i,n,t-1} + a_6 \ln TP_{i,n,t} + a_7 \ln MP_{i,n,t} + a_8 \ln SR_{n,t} + \mu_{i,n,t}\end{aligned} \tag{4-1}$$

where $Z_{i,n,t}$ refers to an invention or a new idea for technology i in country n and time t, $CC_{i,n,t}$ stands for technological diffusion, $EXP_{i,n,t}$ is the export flow of renewable energy,

$IMP_{i,n,t}$ is the import flow of renewable energy, $DKS_{i,n,t-1}$ and $OKS_{i,n,t-1}$ are the previous domestic and overseas knowledge stock, respectively, $TP_{i,n,t}$ refers to the technology-push policy, $MP_{i,n,t}$ is the market-pull policies, $SR_{n,t}$ stands for science resources, and $\mu_{i,n,t}$ is an error term.

Depending on the signs and significance of a_2 and a_3, this study estimates the effect of international trade on R&D activity. If $a_2 > 0$, the decision for R&D may be affected by increases in export flows, with the firms' expectation of increased profits. In addition, if $a_3 > 0$, more R&D activity may be induced through intended knowledge spillover from activities such as the reverse engineering of imported equipment. Meanwhile, if the coefficient of a_3 shows a negative sign, one might infer that in the short run, firms will prefer to import renewable energy technologies rather than engage in R&D owing to technological uncertainties and the high investment cost for R&D, and therefore R&D investment will be substituted with the import of renewable energy-related facilities.

The coefficients of a_4 and a_5 show the elasticity of R&D activity with respect to domestic and overseas knowledge externality, respectively. To calculate two knowledge stocks in Eq. (4-1), the fundamentals and functions of Eqs. (3-2) and (3-3) are kept intact, and therefore the signs and significance of the coefficients will be similar with the results obtained in the previous section.

In addition, there will be little difference between the policy variable impacts a_6 and a_7 and the results of the invention model in the previous section.

4.3.2 Trade model: interrelations between domestic innovation system and international trade

Following Lim's (2011) study, this study establishes import and export models based on a gravity equation. The gravity equation introduced by Tinbergen (1962) is a conventional and basic theoretical model to account for bilateral trade between two economic units, and involves the relevant economic size and distance between the locations (Costantini and Crespi, 2008). Eq. (4-2) shows that the trade flows from the origin *m* to the destination *n* can be described by a function related to the economic size of *m* and *n*, and it is inversely related to the distance between them.

$$F_{mn} = G\frac{M_m^{\alpha} M_n^{\beta}}{D_{mn}^{\theta}}$$

(4-2)

where F_{mn} represents the flow from the origin *m* to the destination *n*; M_m^{α} and M_n^{β} indicate the economic size of *m* and *n*, respectively, measuring their gross domestic products; D_{mn}^{θ} is the distance between *m* and *n*; and G stands for the further determinants that affect the flow.

In this study, the trade flows (i.e., F_{mn}) account for both import and export activities, and the scope of the trade flows is assumed to be the flows between country *n* and the world (the flow from the origin *i* to the world representing exports, and the flow from the world to the destination *i* representing imports). This study constructs an empirical import activity model, modifying Eq. (4-2) and transforming it in log term as follows:

$$\ln IMP_{i,n,t} = d_0 + d_1 \ln CC_{i,n,t} + d_2 \ln DKS_{i,n,t} + d_3 \ln MP_{i,n,t} + d_4 \ln FPRI_{n,t} + d_5 \ln TEG_{n,t} + \rho_{i,n,t}$$

(4-3)

where $IMP_{i,n,t}$ stands for the import flows from the world to the destination *n* for technology *i* in time *t*, $DKS_{i,n,t}$ is the domestic knowledge stock including R&D activity in time *t*, $CC_{i,n,t}$ is the technological diffusion, $MP_{i,n,t}$ is market-pull policies, $FPRI_{n,t}$ is fossil fuel price, $TEG_{n,t}$ is domestic electricity production, and $\rho_{i,n,t}$ is an error term.

This study adopts the domestic knowledge stock as the endogenous variable, because an increase in the domestic knowledge stock will enable the domestic technologies and facilities related to renewable energy to improve their competitiveness, which may lead to decreases in imports. Therefore, I expect a negative sign for d_2. However, if $d_1 > 0$, the more the renewable energy technologies diffuse and the farther the domestic market of renewable energy expands, the more the quantum of advanced or cost-effective equipment and components that can be imported. In addition, the market-pull policy variables are included in Eq. (4-3) to determine the direct market-pull policy impacts on imports.

In the case of the import model, this study assumes that the decision to import renewable energy-related technology or components from abroad will depend on the domestic market and the technological potential of renewable energy, and therefore the control variables ($FPRI_{i,n,t}$ and $EPRO_{i,n,t}$) will reflect the characteristics that affect the domestic market conditions of renewable energy.

Meanwhile, the export model can be described as a function of the domestic knowledge stock, technological diffusion, market-pull policies, and domestic and foreign economic size as follows:

$$\ln EXP_{i,n,t} = e_0 + e_1 \ln CC_{i,n,t} + e_2 \ln DKS_{i,n,t} + e_3 \ln MP_{i,n,t} + e_4 \ln GDP_{n,t} + e_5 \ln GFP_{n,t} + \lambda_{i,n,t}$$

(4-4)

where $EXP_{i,n,t}$ stands for the export flows from the origin n to the world for technology i in time t, $DKS_{i,n,t}$ is the domestic knowledge stock, $CC_{i,n,t}$ is the technological diffusion, $MP_{i,n,t}$ is the market-pull policies, $GDP_{n,t}$ is the domestic economic size, $GFP_{n,t}$ is the foreign economic size, and $\lambda_{i,n,t}$ is an error term.

In contrast to the effect of endogenous variables on imports, the domestic knowledge stock is expected to increase the flow of exports, because innovation and the development of new technology will encourage export competitiveness to be strengthened and new markets abroad to be explored. In addition, the domestic diffusion of technologies will also affect the performance of exports by the economy of scale through market expansion. Therefore, if $e_1 > 0$ and $e_2 > 0$, one can infer that the flow of exports will be positively influenced by domestic technological change.

In the case of the export model, the decision to export renewable energy-related technologies or facilities will depend on not only the domestic economic size but also on the world economic size. In other words, the farther the world market expands (i.e., the more the foreign economic size grows), the more the potential of the export market to increase, which may affect the export performance of the origin country *n*. Therefore, control variables ($GDP_{i,n,t}$ and $GFP_{i,n,t}$) are used to evaluate the domestic and foreign economic market sizes.

4.3.3 Aggregated model based on endogenous R&D activity and technological diffusion

As shown in the research framework in Fig. 1.1, the sustainable growth model contains the three stages of the domestic innovation system and two additional stages, that is, export and import activities. To connect the domestic and foreign systems, I consider R&D as the link between the two systems, because R&D, as the resource of domestic innovation, uses the existing information and resources more effectively by trading and enhances productivity by taking advantage of foreign technological advancements (Coe and Helpman, 1995). In return, an intensive R&D can give a positive response to export activities. In addition, domestic technological diffusion can be regarded as an endogenous variable due to the interrelations between domestic and foreign markets.

To build a sustainable growth model, this thesis aggregate five simultaneous equations, Eqs. (3-9), (3-14), (4-1), (4-3), and (4-4), and the estimates by the three-stage least squares (3SLS) technique that considers not only the endogeneity but also the correlation among equations. In the five simultaneous equations, the endogenous variables are $Z_{i,n,t}$, $SC_{i,n,t}$, $CC_{i,n,t}$, $EXP_{i,n,t}$, and $IMP_{i,n,t}$, and other than the endogenous variables, the instrument variables used in the 3SLS techniques are all exogenous explanatory variables.

4.4 Data

A cross-section of the panel data consists of some countries in the OECD: sixteen countries in solar PV—Australia, Austria, Canada, Denmark, France, Germany, Italy, Japan, Korea, Netherlands, Norway, Spain, Sweden, Switzerland, the United Kingdom, and the United states—and fourteen countries in wind power—Austria, Canada, Denmark, Finland, Germany, Italy, Japan, Netherlands, Norway, Spain, Sweden, Switzerland, the United Kingdom, and the United states. Unbalanced data for these countries are collected for the periods 1991–2007 for solar PV and 1997–2008 for wind power.

To measure invention ($Z_{i,n,t}$), this study assumes that an invention is expressed as the proportion of patent applications for renewable technology to the total patent applications. The patent applications filed under the Patent Cooperation Treaty (PCT) where collected from the *OECD iLibrary* database (2011a).

The dependent variables for international trade, $IMP_{i,n,t}$ and $EXP_{i,n,t}$, are measured as the amount of the country's imports (based on Cost, Insurance and Freight, CIF) and exports (based on Free on Board, FOB) (US$), which are available from the United Nations Commodity Trade Statistics Database (UN Comtrade database). The import and export data refer to the photosensitive and photovoltaic devices (HS1992, Commodity list code: 8541.40) for solar PV technology and wind powered-generating set (HS1996, Commodity list code: 8502.31) for wind power technology.

Figures 4.2 and 4.3 show the export trends for solar PV and wind power, respectively.

For solar PV, Japan has the highest amount of exports, growing steeper from the early 2000s, with Germany and the United States following. For wind power, Denmark has been the major country leading the export market until the middle 2000s, with Germany showing a steep growth after the early 2000s. I might infer that these countries experience a steep export growth as well as an increase in domestic capacity since the 2000 owing to the development of their domestic industries and various government supports.

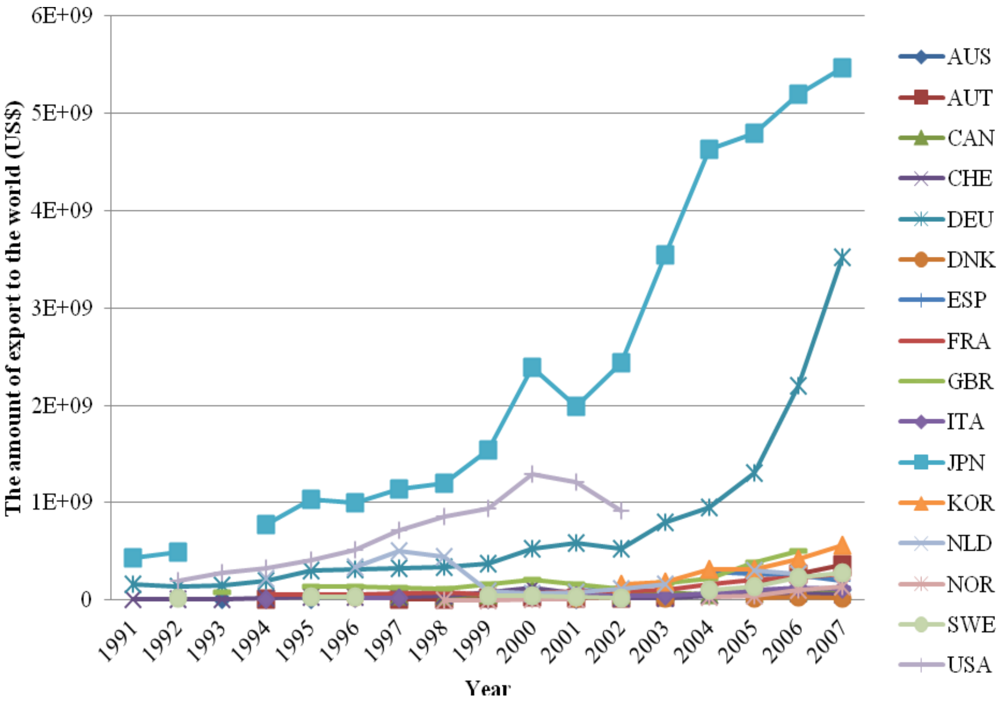


Figure 4.2 Trend of export flows for solar PV technology

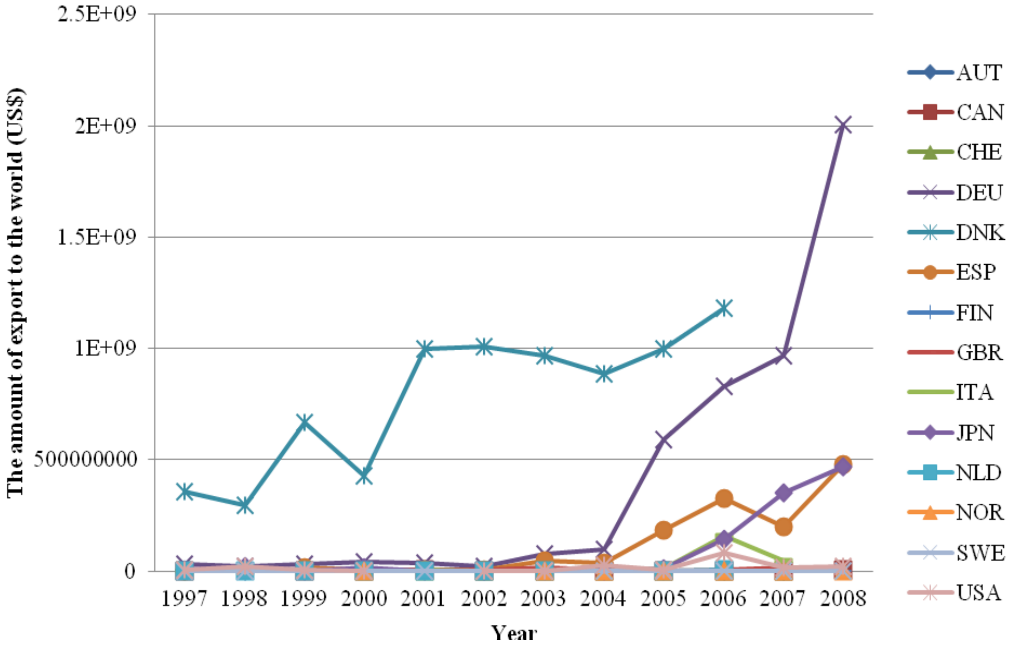


Figure 4.3 Trend of export flows for wind power technology

Figures 4.4 and 4.5 illustrate the import trends for solar PV and wind power, respectively. For both technologies, Germany and the United States are dominant countries, importing equipment. Both before and after 2005, when the Kyoto protocol was enacted, international trade shows a rapid growth with increases in domestic technology diffusion.

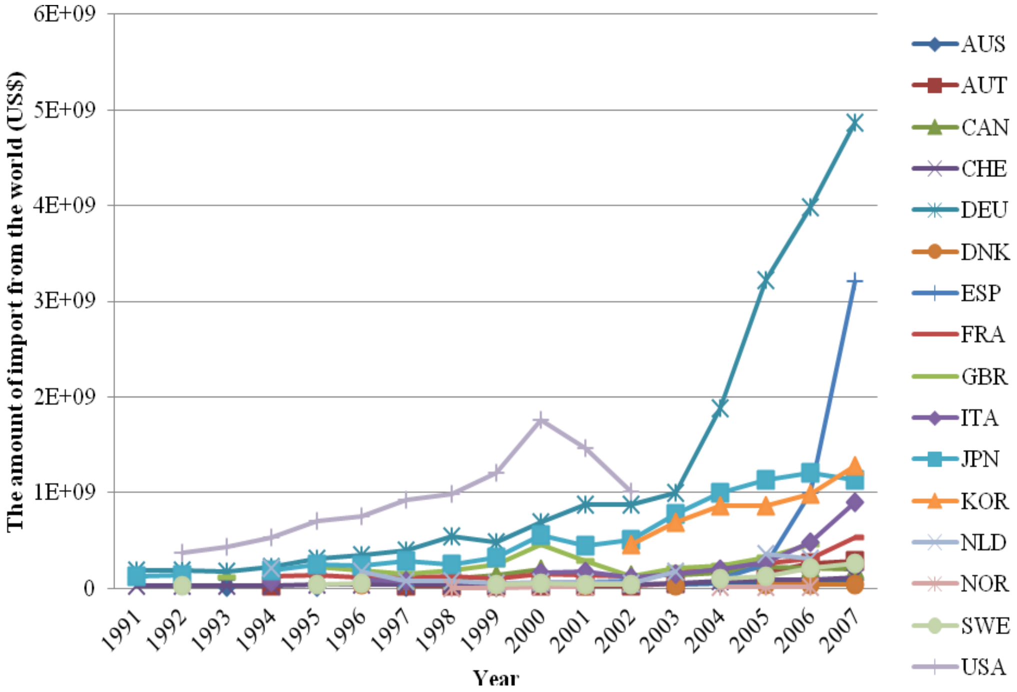


Figure 4.4 Trend of import flows for solar PV technology

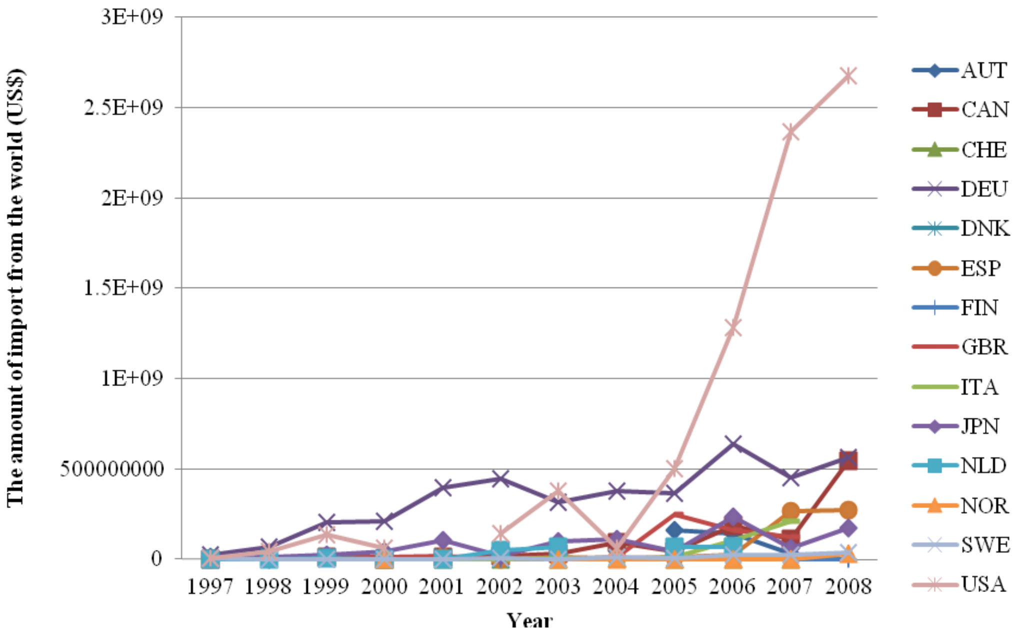


Figure 4.5 Trend of import flows for wind power technology

As explanatory variables, the domestic knowledge stock ($DKS_{i,n,t}$) and overseas knowledge stock ($OKS_{i,n,t}$) are built on PCT applications. For the market expansion variable, $CC_{i,n,t}$, I consider cumulative (installed) capacity (Megawatt). The data of cumulative capacity for solar PV technology are available from the 2008 volume of the series published by IEA-PVPS (1992–2008) and IEA (2009c), whereas the data for wind power are available from the 2008 volume of the series published by IEA (1998–2008) and IEA (2009c).

For policy variables, this study considers public R&D as the instrument supporting technology push ($TP_{i,n,t}$), and public investment, tariff incentives, renewable energy obligations, and environmental taxes as the instruments promoting market pull ($MP_{i,n,t}$). I regard public R&D budgets (million US$, 2009 prices and PPP) as a technology-push policy ($TP_{i,n,t}$). These data are drawn from the public R&D budget, disaggregated by type of technology in the *Energy Technology R&D Budget 2010 edition,* within IEA's database (IEA, 2011b).

The variables for market-pull policies are measured by dummy variables. A dummy variable of a policy equals 1 if the policy is implemented and zero if the policy is not implemented. The data of these policies are taken from the IEA (2004) and IEA/IRENA (2011) online databases.

For control variables, the population data, $POP_{n,t}$, are taken from the *OECD iLibrary* database (2011b). For import flow control, I use the international price of coal (US$/ton) as the fossil fuel price ($FFP_{n,t}$), since coal takes the largest share in electricity generation, at 40.6% in 2009 (IEA, 2011d). The data of the total price of steam coal used in the national electricity sector are drawn from IEA (2009b). The total amount of electricity generation ($TEG_{n,t}$) and gross domestic production ($GDP_{n,t}$) are taken from the electricity total gross production (GWh) data in IEA (2009a) and the GDP data (US$, 2005 prices) from the OECD *iLibrary* database (2011b), respectively. The variable of gross foreign products ($GFP_{n,t}$) is calculated by summing the GDPs of all the countries other than country n. Tables 4.1 and 4.2 present the basic descriptive statistics for all the variables used in the empirical analysis.

Table 4.1. Descriptive statistics in solar PV

Variable (Obs.105)	Mean	Std. Dev	Min	Max
Explanatory variables				
Patent proportion (%)	0.29	0.20	0.01	0.95
Import (million US$)	5.26e+8	7.85e+8	8.60e+6	4.90e+9
Export (million US$)	6.28e+8	1.10e+9	6.20e+6	5.50e+9
System cost(2000 US$/kW)	9418.19	4299.60	4150.54	26385.79
Cumulative capacity (MWe)	217.62	576.58	1.5	3835.5
Domestic knowledge stock (t)	45.84	75.22	0.52	451.29
Domestic knowledge stock (t-1)	36.16	60.55	0.00	403.32
Overseas knowledge stock (t-1)	510.25	354.49	27.13	1191.06
Overseas knowledge stock (t)	634.41	442.71	44.03	1504.99
Absorption capacity	0.65	1.34	2.89e-6	4.63
Policy variables				
Public R&D (2009 million US$)	29.80	35.58	0.36	165.58
Tariff incentives (dummy)	0.43	0.50	0	1
Renewables Obligation (dummy)	0.34	0.48	0	1
Environmental taxes (dummy)	0.29	0.45	0	1
Public investment (dummy)	0.32	0.47	0	1
Control variables				
Science resource	7.32	2.09	2.8	11.9
Raw material prices (US$/kg)	71.63	49.87	17.5	177
Coal prices (US$/tonne)	38.14	6.15	30.73	48.41
Electricity generation (GWh)	6.59e+5	8.98e+5	36243	4.05e+6
Gross domestic production (2005 million US$)	2.15e+6	2.46e+6	1.70e+5	1.15e+7
Gross foreign production (2005 million US$)	9.30e+7	1.47e+8	1.90e+7	6.70e+8

Table 4.2. Descriptive statistics in wind power

Variable (Obs.44)	Mean	Std. Dev	Min	Max
Explanatory variables				
Patent proportion (%)	0.35	0.54	0.02	2.35
Import (million US$)	8.86e+7	2.14e+8	1001	1.28e+9
Export (million US$)	9.98e+7	2.76e+8	512	1.20e+9
System cost(2000 US$/kW)	1188.60	257.90	778.96	1995.08
Cumulative capacity (MWe)	2610.75	3654.44	38	18428
Domestic knowledge stock (t)	24.91	27.02	1.81	125.26
Domestic knowledge stock (t-1)	20.30	24.45	1.10	123.04
Overseas knowledge stock (t-1)	210.92	116.90	48.87	429.48
Overseas knowledge stock (t)	256.24	121.11	55.75	451.06
Absorption capacity	0.45	0.62	0.01	2.05
Policy variables				
Public R&D (2009 million US$)	12.94	15.00	0.13	48.63
Tariff incentives (dummy)	0.34	0.48	0	1
Renewables Obligation (dummy)	0.47	0.51	0	1
Environmental taxes (dummy)	0.47	0.51	0	1
Public investment (dummy)	0.14	0.35	0	1
Control variables				
Science resource	7.36	2.52	2.8	13.4
Raw material prices (US$/metric tonne)	348.41	130.98	200	600
Coal prices (US$/tonne)	35.63	4.76	30.73	45.7
Electricity generation (GWh)	9.59e+5	1.43e+6	37726	4.3e+6
Gross domestic production (2005 million US$)	3.05e+6	4.04e+6	1.41e+5	1.29e+7
Gross foreign production (2005 million US$)	2.59e+7	4.14e+6	1.61e+7	3.20e+7

4.5 Empirical Results

4.5.1 Sustainable system with domestic innovation and international trade

This study builds an empirical model to determine the sustainable growth system with interrelations between domestic innovations and international trade. The model gives significant results, as shown in Table 4.3, 4.4, 4.5, 4.6, and 4.7.

Above all, a comparison of these results with the results obtained using the domestic innovation model in Chapter 3, indicates some differences in the estimated values of coefficients and in the degree of significance, which can be attributed to the structural difference of equations. Nevertheless, one finds that the two models show generally similar results in terms of policy impacts and interactions in the invention, innovation, and diffusion stages. This implies that the two models are robust[25].

From Tables 4.3 to 4.5, in both technologies, the endogenous variables to compose the domestic innovation system show significant interactions similar to those obtained in Chapter 3, which make the virtuous cycle in domestic technological change. In the static impact of policies, in general, the technology-push and price-based policies are significant for inventions in both the technologies, but the impact of quantity-based and environmental policies depends on the technology.

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[25] For more details, see Appendix 2 and 3, which compare more models to check for robustness.

As specific assessment of the results, Table 4.3 shows the R&D activity model reflecting international trade. Surprisingly, the interrelations between R&D activity (invention) and international trade depend on the technologies. Specifically, no international trade influences R&D activity in solar PV, but R&D activity in wind power is seen to decline due to imports at a 5% significance level. This suggests that the set of determinants varies with the international processes of renewable energy technology. In renewable energy technology, the more the technology is developed and more the cost is competitive, the more the international market would expand. This leads to increases in the market entry of developing as well as developed countries.

According to Jha (2009), the proportions of exports and imports of solar PV and wind power with respect to total renewable energy in 2007 are 10.6% and 10.2%, and 36.5% and 37.3%, respectively, indicating that the international trade in wind power amounts to three times the trade in solar PV. Therefore, domestic R&D in highly developed technologies may be affected by the international market more sensitively than in less-developed technologies. This implies that the targets and strategies of domestic R&D activity (invention) should be specified by renewable energy technology in order to accomplish economic growth through international trade.

In wind power, which shows an elasticity of 10.4% in R&D activity with respect to imports, one can see the negative response of imports on R&D activity, inferring that in the short run, firms prefer to import renewable energy technologies and equipment rather than engage in R&D owing to high technological uncertainties and investment costs in

R&D. Furthermore, as mentioned above, expansion of the international market may promote imports rather than internal R&D, inducing increases in the supply of cheaper options from the developing countries such as China, which enjoy low labor costs. From this, I infer that there is little knowledge spillover from reverse engineering through the import of foreign equipment or technologies, and imports cannot be considered one of the international spillover channels, but are rather a substitute investment for R&D.

With regard to the other significant variables, domestic diffusion (cumulative capacity) is significant on R&D activity, but spillovers from overseas knowledge is not significant on R&D activity; this is not consistent with the results obtained in the previous chapter. However, the values are positive in both technologies. As policy impact, renewable energy obligations appear to have a positive impact on solar PV, but an insignificant impact on wind power.

Table 4.3. Estimation result of invention model

	Solar PV	Wind power
Explanatory variables		
Export	-0.178	-0.241
	(0.477)	(0.145)
Import	-0.250	-0.104**
	(0.353)	(0.012)
Cumulative capacity	0.381*	1.125***
	(0.098)	(0.006)
Domestic knowledge stock (t-1)	-0.017	-0.606**
	(0.898)	(0.029)

Overseas knowledge stock (t-1)	0.155	0.123
	(0.421)	(0.712)
Policy variables		
Public R&D	0.218**	0.346***
	(0.013)	(0.001)
Tariff incentives	0.360**	0.779*
	(0.043)	(0.082)
Renewables obligations	0.346**	-0.169
	(0.031)	(0.573)
Environmental taxes	-0.199	2.655
	(0.367)	(0.104)
Public investment	-0.225	-0.233
	(0.197)	(0.719)
Control variables		
Science resources	0.452	2.376**
	(0.637)	(0.049)
Constant	-1.769	-13.694***
	(0.547)	(0.000)
R^2	0.725	0.861
Learning-by-using rate	0.232	0.542

Note: The number in parentheses refers to p-value and asterisks indicate statistical significance, i.e., * p<0.1, ** p<0.05 and *** p<0.01.

Table 4.4 shows the results of the innovation model. As expected, two endogenous variables, technological diffusion and domestic knowledge stock, induce reduction in costs through learning-by-doing and learning-by-searching, respectively. Interestingly, strengthening the absorption capacity is seen to reduce costs in wind power, when considering the interrelations between domestic innovations and international trade. I believe that this is because the endogeneity of foreign trade may affect the impact of overseas knowledge stock on both the invention and innovation models. A deeper analysis of this result could be the subject of future research.

With regard to the static impact of policies, tariff incentives may increase cost differences, but have insignificant results in the domestic innovation model. Competition-inducing instruments, for example, the renewable energy obligations and environmental taxes, have positive impacts on reducing the system costs in solar PV and wind power, significant at the 5% level. Although environmental taxes on solar PV appear to be insignificant, its actual significance approaches almost the 10% level.

Table 4.4. Estimation results of innovation model

	Solar PV	Wind power
Explanatory variables		
Cumulative capacity	-0.210***	-0.084***
	(0.000)	(0.000)
Domestic knowledge stock (t)	-0.098***	-0.095**
	(0.007)	(0.028)
Overseas knowledge stock (t)	-0.026	0.026
	(0.424)	(0.408)
Absorption capacity	0.028	-0.649***
	(0.708)	(0.000)
Policy variables		
Tariff incentives	0.112*	0.149**
	(0.097)	(0.012)
Renewables obligations	-0.127**	0.062

	(0.044)	(0.189)
Environmental taxes	-0.111	-0.236**
	(0.110)	(0.013)
Public investment	-0.202***	0.114*
	(0.000)	(0.074)
Control variables		
Raw material prices	0.178***	0.308***
	(0.000)	(0.000)
Gross domestic product	0.335***	1.297***
	(0.000)	(0.000)
Constant	4.992***	-12.326***
	(0.000)	(0.143)
R^2	0.800	0.893
Learning-by-doing rate	0.135	0.057
Learning-by-searching rate	0.066	0.064

Note: The number in parentheses refers to a p-value and asterisks indicate statistical significance: * p<0.1, ** p<0.05, and *** p<0.01.

Table 4.5 shows the results of the diffusion model. There is little difference between the sustainable growth model and the domestic innovation model. In wind power, tariff incentives are significant, with a positive impact on diffusion, but environmental taxes are not significant.

Table 4.5. Estimation results of diffusion model

	Solar PV	Wind power
Explanatory variables		
System cost	-3.300***	-2.655***

	(0.000)	(0.000)
Policy variables		
Tariff incentives	0.942***	0.813**
	(0.001)	(0.040)
Renewables obligations	-0.326	0.662**
	(0.275)	(0.014)
Environmental taxes	-0.686**	-0.516
	(0.026)	(0.370)
Public investment	-0.586**	0.793**
	(0.041)	(0.039)
Control variables		
Fossil fuel prices	1.983***	4.793***
	(0.000)	(0.000)
Electricity generation	1.238***	-0.075
	(0.000)	(0.856)
Constant	10.403**	8.966*
	(0.016)	(0.060)
R^2	0.819	0.905

Note: The number in parentheses refers to a p-value and asterisks indicate statistical significance: * $p<0.1$, ** $p<0.05$, and *** $p<0.01$.

As shown in Table 4.6, domestic technological diffusion (or market expansion) can be considered one of the major dominant factors affecting imports, showing significances at the 1% and 5% levels for solar PV and wind power, respectively. The imports for solar PV and wind power increased by 42.7% and 117.1%, respectively, for every 1% increase in domestic technological diffusion, implying that import activities in wind power are more elastic in terms of domestic market expansion. This could be because of the higher trade dependence in the market due to more competition and the more developed wind power technology.

In contrast to domestic technological diffusion, the accumulation of domestic knowledge plays a key role in reducing the import of technologies or equipment, which is significant at the 10% level for solar PV and 1% level for wind power. From Table 4.3, I infer that solar PV in the early stage of development concentrates on R&D for domestic cost reduction and new technology development. This is based on the empirical results that R&D activity in solar PV scarcely responds to international trade but cuts down imports by increasing the stock of domestic equipment through competitive pricing. However, R&D activity in wind power has a positive impact on decreasing imports, as well as responds to international trade, implying that R&D activity in wind power interrelates with the international market. In other words, the more developed a technology is, the more open it is to the global market due to increased competition in the domestic market. This view is supported by Jha (2009), who stressed that an intensified competitive market in wind turbines encourages firms to produce more and trade globally. While considering the further expansion of the domestic market or the cheaper options and equipment for renewable energy available in the foreign market, it is found that more imports flow from the foreign markets to the domestic market, implying that the aims of R&D activity vary by renewable energy technology.

With regard to policy impacts, as expected, the renewable energy obligations and public investments are major factors increasing the imports of both the technologies. I find that competition-inducing policies may exert greater pressure on the developers to acquire the best available locations, and due to a number of uncertainties and high transaction costs, this may push the producers toward short-term imports of cheap foreign equipment rather than inventions through R&D (Mitchell, 2000; Ibenholt, 2002; Menanteau et al., 2003; Meyer, 2003; Lauber, 2004). In wind power, tariff incentives also appear to increase imports, because a firm encourages the import of cheaper equipment to maximize its profits under guaranteed prices.

Further, a set of control variables appears to have a positive impact on import flows. I find that the higher the fossil fuel prices rise and more the electricity produced, the more the equipment or technologies for renewable energy imported.

Table 4.6. Estimation result of import model

	Solar PV	Wind power
Explanatory variables		
Cumulative capacity	0.427***	1.171**
	(0.000)	(0.045)
Domestic knowledge stock	-0.178*	-3.909***
	(0.077)	(0.000)
Policy variables		
Tariff incentives	0.232	2.782*
	(0.138)	(0.091)
Renewables obligations	0.463***	2.340*
	(0.001)	(0.060)
Environmental taxes	-0.256	1.470
	(0.109)	(0.533)

Public investment	0.302**	5.672***
	(0.013)	(0.001)
Control variables		
Fossil fuel prices	0.851***	5.765
	(0.000)	(0.118)
Gross domestic product	0.565***	10.460***
	(0.000)	(0.000)
Constant	7.118***	-156.589***
	(0.000)	(0.000)
R^2	0.917	0.727

Note: The number in parentheses refers to p-value and asterisks indicate statistical significance, i.e., * p<0.1, ** p<0.05 and *** p<0.01.

Table 4.7 shows the response of export flows with respect to domestic diffusion of technology and knowledge stock. For solar PV, the domestic knowledge stock acts as one of the dominant factors increasing exports, and is significant at the 1% level. The elasticity of exports with respect to the domestic knowledge stock of solar PV is 42.9%. This implies that the technologies with low cost competitiveness and in the early stage of development strengthen foreign competitiveness by enhancing their cost competitiveness and developing new technologies through R&D.

However, wind power shows a different result: domestic technological diffusion leads to increases in exports, but knowledge stock is insignificant. This could be because, as mentioned above, wind power is more open to the global market and is germane to international trade.

With regard to policy impact, competition-inducing instruments have a positive impact on export flows. For solar PV, renewable energy obligations stimulate the export of equipment as well as imports. I infer that solar PV firms try to diversify their business fields (or diffusion channels) and secure global markets through exports, because renewable energy obligations may work disadvantageously for the domestic diffusion of technology in the early stage of development in solar PV. This applies also to wind power. Wind power experiences significant increases in exports from environmental taxes. As the wind power market is more competitive by environmental policy, wind power firms try to diversify their business channels and distribute their resources and outcomes more efficiently.

From empirical results shown in Tables 4.3 to 4.7, it is seen that a virtuous cycle is formed between domestic innovations and export activity for both solar PV and wind power. In other words, domestic R&D activity and technological diffusion increases an economy's exports, and the profit growth through increased exports simultaneously returns the R&D investment. This is consistent with the argument of Aw et al. (2008): "R&D investment, through its effect on future productivity, increases the profits from exporting, and participation in the export market raises the return to R&D investments."

From these results, it can be concluded that domestic technological diffusion and R&D activity play an important role in the globalization of technology and are the basis of domestic innovation, through which sustainable economic growth can be realized. However, the specific mechanisms and interactions in a sustainable growth system vary by technology.

Table 4.7. Estimation result of export model

	Solar PV	Wind power
Explanatory variables		
Cumulative capacity	-0.042	2.090***
	(0.748)	(0.000)
Domestic knowledge stock	0.429***	-0.788
	(0.006)	(0.318)
Policy variables		
Tariff incentives	-0.006	1.903
	(0.978)	(0.103)
Renewables obligations	0.672***	-0.885
	(0.003)	(0.332)
Environmental taxes	-0.511**	8.469***
	(0.037)	(0.000)
Public investment	0.543***	-1.581
	(0.005)	(0.203)
Control variables		
Gross domestic products	0.385**	3.504**
	(0.014)	(0.045)
Gross foreign products	0.227***	-4.251
	(0.006)	(0.564)
Constant	7.955***	23.751
	(0.003)	(0.866)
R^2	0.836	0.836

Note: The number in parentheses refers to p-value and asterisks indicate statistical significance, i.e., * p<0.1, ** p<0.05 and *** p<0.01.

4.5.2 Dynamic impact of renewable energy policies for sustainable growth

These results also show the effects of renewable energy-related policies on each stage by technology. As this study considers endogenous R&D activity and domestic technological diffusion, the policies may affect both exports and imports through market expansion and R&D activity. As shown in Tables 4.8 and 4.9, when considering the virtuous cycle between domestic innovation and international trading, the impact of policies can vary by policy circulation. In the invention, innovation, and diffusion stages, the simulation results generally show similar policy impacts on the domestic innovation system.

The technology-push and price-based policies influence dynamic positive impacts on not only domestic innovation but also export activity. Quantity-based policies also stimulate domestic innovation and foreign competitiveness. In addition, the dynamic impact of public investment appears to be positive over the sustainable growth of solar PV and wind power technology. Although these policies have different static impacts on each stage, the renewable energy policies can be regarded as important instruments to accomplish sustainable economic growth.

Interestingly, there are two significant differences in the dynamics of policy impacts due to the difference in technological development levels. First, environmental policies such as environmental taxes play different role, depending on the technology. The sign of environmental taxes becomes negative in solar PV technologies, but is significant in wind power technologies. Environmental policies help wind power to continue sustainable innovation and technological diffusion by directly reducing system costs and enhancing export activities in the long-term. The policies increase the domestic demand of technology through higher price-competitiveness, and thereby provide wind power firms with favorable production conditions. However, solar PV does not enjoy benefits from environmental policies, because solar PV with low cost competitiveness will have a disadvantage in technological diffusion and exports when environmental policies are introduced.

Second, renewable energy policies stimulate import activities as well as export activities in solar PV, whereas they reduce import activities in wind power. In the solar PV industry, the firms may prefer to import already-developed equipment, rather than engage in R&D, from the existing market, because firms in the early stage of technological development would wish reduce the uncertainty of R&D and increase their market share efficiently. However, in the wind power industry, the firms will be able to substitute the import of equipment with R&D activity as the domestic wind power technology develops and diffuses. Thus, government policies play a key role in improving the domestic and foreign competitiveness and lead to reduction in imports.

Table 4.8. Simulation result for estimating dynamic effect of the policies in solar PV technology

Policy	Invention		Innovation (Cost)		Diffusion		Export		Import	
	Static effect	Dynamic effect	Static effect	Dynamic effect	Static effect	Dynamic effect	Static effect	Dynamic effect	Static effect	Dynamic effect
Technology push policy										
Public R&D	0.218	0.364	N.A	-0.116	N.A	0.384	N.A	0.156	N.A	0.099
Market pull policies										
Tariff Incentives	0.360	1.788	0.112	-0.850	0.942	3.747	-	0.767	-	1.282
Renewables Obligations	0.346	1.447	-0.127	-0.875	-	2.889	0.672	1.293	0.463	1.439
Environmental Taxes	-	-1.422	-	0.923	-0.686	-3.732	-0.511	-1.121	-	-1.340
Public Investment	-	0.167	-0.202	-0.310	-0.586	0.438	0.543	0.615	0.302	0.459

Note: '-' indicates an insignificant impact.

Table 4.9. Simulation result for estimating dynamic effect of the policies in wind power technology

Policy	Invention		Innovation (Cost)		Diffusion		Export		Import	
	Static effect	Dynamic effect	Static effect	Dynamic effect	Static effect	Dynamic effect	Static effect	Dynamic effect	Static effect	Dynamic effect
Technology push policy										
Public R&D	0.346	1.292	N.A	-0.158	N.A	0.419	N.A	0.877	N.A	-4.559
Market pull policies										
Tariff Incentives	0.779	3.841	0.149	-0.366	0.813	1.784	-	3.729	2.782	-10.143
Renewables Obligations	-	2.283	-	-0.351	0.662	1.593	-	3.330	2.340	-4.719
Environmental Taxes	-	3.021	-0.236	-0.673	-	1.787	8.469	12.204	-	-9.716
Public Investment	-	0.161	0.114	0.041	0.793	0.683	-	1.428	5.672	5.842

Note: '-' indicates an insignificant impact.

4.6 Conclusion

In order to consider renewable energy technologies as instruments for sustainable economic growth as well as environmental solution, it is important to determine not only the domestic diffusion of renewable energy technologies but also foreign trade competitiveness. In addition, the renewable energy-related policies concentrate on an economy's domestic innovation and diffusion of renewable energy technologies and indirectly affect its exporting and importing performance through R&D activity and market expansion. Therefore, this study tries to find the interrelations between domestic innovation and international trade, and determines the role of renewable energy-related policies in this system.

Our estimation results show that the interrelations between R&D activity, domestic technology diffusion, and international trade, especially the dependence of R&D activity on international trade, vary by renewable energy technologies, which may be owing to the differences in international technology processes. Overall, I find that highly advanced domestic R&D activity may be affected by international markets more sensitively than less advanced technologies.

In addition, I infer that the aim and role of R&D activity is related to the technological development level. This implies that the target and strategies of domestic R&D activities (invention) should be specified by the renewable energy technology in order to accomplish economic growth through international trade. Solar PV in the early stages of technological development needs to concentrate on R&D activity for domestic cost reduction and promote domestic technological diffusion in order to strengthen foreign competitiveness. The technology in advanced stages, such as wind power technology, aims to exploit the international market with the development of new or advanced technology, as there is a lot of competition in the domestic market. This technology should increase investments in R&D activities in order to strengthen foreign competitiveness.

We find that the more the domestic R&D activity and technological diffusion intensifies, the more the flow of exports to the world, and a virtuous cycle forms between domestic innovation and international trade. This virtuous cycle can help the technologies in the early stages to grow to higher levels, and therefore it is necessary to introduce various instruments that support R&D activity and high global competitiveness.

The implications of renewable energy-related policies for foreign competitiveness would suggest that although the impacts of the policies vary by technology, the renewable energy obligations are significant instruments for increasing the access opportunities to international markets, leading to more exports and imports in solar PV. In wind power, environmental taxes stimulate export activity. In Chapter 3, it is shown that these policies have a common static impact, that is, they are positive on innovation. This implies that domestic market price-related factors are linked to foreign trade, and competition-inducing instruments directly lead to not only cost decreases but also higher foreign competitiveness in the short run.

While considering the policy impact dynamics, the renewable energy policies are significant and effective instruments for increasing foreign competitiveness as well as domestic innovations. Environmental policies can be considered important instruments for advancing renewable energy technologies. In terms of a route for a policy to affect export activities, when introducing renewable energy policies, the firms should invest more in R&D activities in order to reduce costs, which could result in increased export flows in solar PV. Furthermore, environmental policies will enable the entry of more new wind power firms in the market, resulting in increased exports.

Chapter 5. Conclusions and Implications

5.1 Summary of the Results

The investment for clean energy technologies is becoming more important in view of global climate changes, and there is a rapid increase in technological development. However, private R&D investments in this field are lower than the socially optimal level owing to market failures, resulting in stagnation in the spread of energy efficient technologies, that is, causing an energy efficiency paradox. The governments have implemented several technology-push and market-pull policies to overcome the market failure problem and achieve innovations in clean energy technologies.

The goal of this thesis is to model the social phenomenon, that is, the market failure-energy efficiency paradox, and assess the impact of government policies on the process of domestic technological change and foreign competitiveness in clean energy technologies through empirical analysis using a variety of techniques.

Chapter 2 determines the global trends in carbon dioxide emission and six underlying forces that drive the emissions from the industrial sector using production-based decomposition methods during the period 1990–2006. A cross-country analysis is also conducted to identify each country's technical potential for improving its CO_2 intensity. The model provides more detailed information about the influence of both production-based technical efficiency and the technological changes on CO_2 emissions, and therefore, shows that the relative degree of each country’s energy efficiency paradox can be determined empirically.

This chapter shows that the total industrial CO_2 emissions generally decrease in OECD countries, while the emissions increase in non-OECD countries. In an overall trend, increased economic activities have been the dominant driver of CO_2 emissions, while changes in the potential energy intensity and energy mix have contributed to emission reductions in the majority of OECD and non-OECD countries.

With regard to the impacts of production technology (i.e., the impacts of technical efficiency and technological change), this study gives mixed results, but generally shows that OECD countries diffuse their production technologies more efficiently than do non-OECD countries. In the time-series aspect of the study, both OECD and non-OECD countries have experienced the efficiency paradox emerging from the gap between the existence of both the most efficient technologies and their adoption by the industry due to increase in fossil fuel consumption and no regulations to mitigate GHG emissions during the period 1990–1998. However, since 1998, when the Kyoto protocol was introduced, the OECD countries are obliged to reduce their GHG emissions and improve their energy usage efficiency, and to introduce best-practice technologies for energy saving by establishing new energy policies and strengthening environmental policies.

Specifically, the Northern and Western Europe countries, the OECD nations of Asia, and North America do experience the energy efficiency paradox but to a less extent compared to other regions. The Eastern Europe and non-OECD regions have not innovated activities for new energy technologies until recently.

From the perspective of emission mitigation potentials, the study also identifies that many OECD and non-OECD countries have demonstrated a reduced potential for mitigation over time, which can be interpreted to mean that they have enhanced their internal capabilities to improve their production technical efficiency. However, this shows that the OECD countries diffuse their production technologies more efficiently than non-OECD countries. This partially agrees with the decomposition results.

Chapter 3 identifies simultaneous interactions in an endogenous technological-change system and analyzes empirically the static and dynamic impacts of renewable energy policies in solar PV and wind power to find the most effective combination of policies. The empirical analysis is conducted using the 3SLS technique, on the unbalanced panel data of 16 countries for solar PV from 1992 to 2007 and 13 countries for wind power from 1991 to 2006.

The empirical results indicate that the policy outcomes create a virtuous cycle in the technological change system, which can be explained by the systematic process as follows. In the first step, market pull policies create an initial market to introduce renewable technology and technology push policies induce producers to overcome technological barriers more easily. In the second step, diffusion of renewable technologies through market expansion leads to lowering the system costs (i.e., through innovation) of renewable energy via two learning effect channels, the production channel and R&D channel. In the last step, innovations (i.e., which reduce costs) through these learning effects lead to increased diffusion of technologies by enhancing price competitiveness and reducing technical uncertainties. As a result, the more the technologies diffuse, the more the learning effects occur, and the technological progress is accelerated by this virtuous cycle.

According to the policy impact results, the static impact of the technology-push and price-based policies are effective on invention, while quantity-based and environmental policies appear to encourage technology innovations (leading to cost reduction). However, when considering the dynamics of policy impacts, a technology-push policy, with international knowledge spillover, appears to play a more vital role over the process of technology change. This finding suggests that domestic R&D efforts, including public R&D, are necessary for adapting overseas knowledge into domestic market conditions as well as for domestic sources of invention.

Both price- and quantity-based policies provide long-term sustainable solutions for development and installation of a technology, but a price-based policy appears to outperform a quantity-based policy due to its inducement of dramatic technological change. This implies that price-based policies along with a technology-push policy can be regarded as a long-term sustainable solution for the development and installation of technology, and therefore policy makers should consider these policies an important requirement in the harmonization of support schemes.

This study also stresses that as the renewable energy technology advances more and more, it will be necessary to enforce policy instruments that induce competition between the renewable energy technologies and out of such technologies, between the broader and more advanced ones. In the early developing stages, a quantity-based policy, which includes renewable energy obligations that induce competition in the renewable energy markets, is efficient for long-term technological change. However, in the middle- and late-developing stages, environmental policies that induce competition in the entire energy market are required, in addition to a quantity-based policy, in order to promote long-term technological change.

Furthermore, it is important to evaluate the interrelationship between international trade and domestic innovation, because a renewable energy technology will be the driving force behind sustainable economic growth through international trade. Chapter 4 expands the domestic innovation system to assess the interactions between domestic innovation, technological diffusion, imports, and exports in the renewable energy industry. In the chapter, simultaneous equations are presented and the role of renewable energy-related policies in the system is determined. This analysis concentrates on the solar PV and wind power technology used to generate electricity and uses the unbalanced panel data on 16 countries for solar PV and 14 countries for wind power during the period 1991–2008.

The results show that the interrelations between R&D activity and international trade vary by renewable energy technologies. From the results, one finds that as the renewable energy technologies develop more and more, the dependence of R&D activity on international trade becomes higher. The R&D activity for wind power appears to be affected by the flow of imports—there is little spillover from the import of foreign equipment or technologies—and import can be considered a substitution for R&D investment.

The above result also indicates that the aim and role of R&D activity can vary by the level of technological development. In order to strengthen foreign competitiveness in solar PV, which is in the early stage of technological development, domestic technological diffusion as well as R&D activity should be promoted. However, as regards the technology in the developed stage, such as wind power, increased R&D investments are required to exploit the international market with the development of new or advanced technology.

This study also found that the more the domestic R&D activity and technological diffusion intensify, the more would the exports flow to the world, and a virtuous cycle would form between domestic innovation and international trade. This virtuous cycle can help the early-stage technologies to grow to higher levels, and therefore it is necessary that various instruments to support R&D activity and high global competitiveness be introduced.

The implications with regard to renewable energy-related policies for foreign competitiveness suggest that although the policy impacts vary by technology, the renewable energy obligations are significant instruments to increase an economy's access opportunities to international markets, leading to more exports and imports in solar PV. With regard to wind power, environmental taxes stimulate export activity. While considering the impact of policies, the renewable energy policies are significant and effective instruments to stimulate higher foreign competitiveness as well as increase domestic innovation. Environmental policies can also be considered important instruments to stimulate highly advanced renewable energy technologies.

5.2 General Conclusions and Implications

To resolve the environmental issues that are gaining attention as important and critical, an understanding of the global GHG emission trends, underlying drivers across the countries, and performance of clean energy technology in GHG emissions is essential. This would help policy makers design effective GHG mitigation polices by finding the weak points and opportunities through analyses of past emission trends and technological effects.

According to the environmental assessment results of this thesis, in recent times, CO_2 emissions are increasing through more economic activities in the developing countries, but many countries in the world are still trying to improve their energy mix and delink the CO_2 emissions problem from economic growth. For example, in a step to improve its industrial structure and energy efficiency, the United States has lowered its emissions intensity in terms of economic growth (GDP) in 2007 to less than half its 1971 level (IEA, 2009d).

However, on a global scale, the technical efficiency and performance of energy saving technologies, which are regarded as important instruments to resolve environmental problems, show a weak influence on CO_2 emission reduction. Although best-practice technologies were developed and used in several frontier countries, diffusion of those technologies across countries appears to be stagnated or delayed, accounting for an energy efficiency paradox because of market failure.

Specifically, in the 1990s, almost every country experienced the energy efficiency paradox due to the increased use of fossil fuel, led by a global economic boom and with no regulations to mitigate GHG emissions. However, the OECD countries have established new energy policies and have strengthened their environmental policies, following the burden levied on them by the Kyoto protocol to mitigate GHG emissions by 1998, and have improved their efficiency gap by adopting the best-practice technologies. However, many non-OECD countries still experience the energy efficiency paradox, because the global regulations do not affect them yet and hence, they are not willing to reduce their GHG emissions.

This indicates that clean energy technologies are not diffused naturally when the technological advances are made by the simple logic of the market, but are spread only when enforced through international regulations such as the Kyoto protocol, and with continued support for national technology diffusion. This implies that to resolve this phenomenon, and to stimulate clean energy technology diffusion, the post-Kyoto protocols need to include non-OECD countries at a global level, and governments need to intervene through policy instruments at the national level.

In fact, many governments expect a technological solution to environmental problems and economic growth, considering the high social and economic costs for reforming their industrial structure, but what is required are rational costs for technological innovation. Therefore, to find an appropriate technological solution for sustainable economic growth, it is necessary to precede assessing the performance of government policies by first assessing the economy's domestic technological innovation, technological diffusion and, furthermore, global competitiveness through international trade.

To determine governments' efforts to support technological innovation and diffusion for clean energy technology, this thesis concentrates on the renewable energy industry, including solar PV and wind power, and identifies the effect of renewable energy policies, applying various approaches, for example, the static and dynamic aspects in terms of policy impacts.

According to this thesis, policy makers should evaluate the impact of policies considering the systematic interrelations of endogenous technological changes. In addition, it is very important to identify the role of policies in the link between international trade, domestic innovation, and technological diffusion for long-term industrial development. The additional integrated model of the foreign trade system obtains results similar to that of the domestic innovation system model in terms of the virtuous cycle of the innovation model and the impact of policies on that system, whose robustness has been secured. As the domestic technological diffusion and R&D activities interact with international trade, more policy implications will be obtained.

This thesis additionally determined a recent market trend and R&D investment in renewable energy, because by using empirical analysis, changes in the global renewable energy condition since the mid-2000 cannot be explained[26]. Despite the global financial crisis in 2009, the markets expanded and equipment investment increased in both solar

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[26] For more details, see Appendix 4.

PV and wind power (IEA, 2009e; UNEP/BNEF, 2011). However, the market has been facing intensifying competition once developing countries including China and India entered the market, and the worsening European debt crisis forces the Asian countries to be growth oriented. In 2010, R&D investments showed an increase of 40% over the 2009 level, but the share of government R&D increased while that of private R&D reduced due to the financial crisis (UNEP/BNEF, 2011). The policy trend shows that a mixed support system tends to help technological development and market growth rather than a single policy, despite national variation. This thesis suggests some novel policy implications through empirical results, considering the recent trends.

Above all, specific systematic interrelations and the role of policies in domestic innovations and international trade depend on the level of technological advancement. Although both highly advanced and less advanced technologies form the virtuous cycle for technological progress in domestic innovation and technological diffusion, the interrelation between R&D and international trade, especially the dependence of R&D on international trade, vary by technological development. This may result from a different international technological process. In the estimation result, the R&D activity of highly advanced technologies responds to the international market. From this, one can infer that the higher an advanced technology develops the more open would the domestic market be to the world, because of intensifying domestic competition as well as improving foreign competitiveness.

In addition, from the export and import model results, one can infer that the technology in the early stage of technological development, such as in solar PV, can reinforce foreign competitiveness with cost reductions through R&D owing to the large potential to innovate technology. However, the technology in a developed stage, such as in wind power, results in increases in export flows through technological diffusion (i.e., market expansion) and decreases in import flows through R&D activity. This implies that an increase in entry of new firms, rising competition in the domestic market, and economy of scale as well as R&D activity may strengthen foreign competitiveness. In other words, technological development enables a technology with low cost competitiveness to strengthen foreign competitiveness, whereas market factors as well as technological development are dominant in a technology with high cost competitiveness.

Therefore, as the first suggestion, this thesis emphasize that each technology should strengthen its technological competitiveness and compensate the lack of foreign trade. In solar PV, it is important to continue to increase R&D investment for new and more efficient technology, because solar PV has a large potential to reduce costs, and technological development can help strengthen foreign competitiveness. Solar PV also must expand the domestic market and diffuse technology further, which would enable it to accomplish economy of scale and stimulate a learning effect. Meanwhile, R&D investment in wind power is lower than in solar PV, at about one-third, owing to a low potential to improve technology (UNEP/BNEF, 2011). Therefore, to exploit the international market and substitute imports, more investments need to be made in wind power to develop new or advanced technologies.

In this context, the role of R&D has great significance, because it supplies an innovative resource for a virtuous cycle in the complete technological change system, and at the same time absorbs foreign technologies and increases global competitiveness as the link between the country's internal and external markets. However, since investments in private R&D may be lower than the social optimal level due to market failures and information uncertainty, the technology-push policies of the government (e.g., public R&D) would be useful to promote national R&D activity.

This direct effort of the government for knowledge generation and new technology can act as a fundamental driving force for long-term technological change. In the dynamics of its impact, the technology-push policies not only encourage knowledge generation directly, but might also exert positive impacts on cost reduction through learning-by-searching, and, furthermore, it is a significant factor for technology diffusion.

Technology-push policies would also stimulate the increase of domestic knowledge, adapting overseas knowledge to the domestic market conditions as well as for domestic invention resources. As this thesis finds, overseas knowledge spillover cannot affect innovations and technology diffusion directly, but influence them indirectly via in-house R&D activity, and so policy makers should not underestimate the role of technology-push policies. While a technology-push policy has a positive impact on export activity, it has more importance for sustainable economic growth. Along with government support for R&D, policy makers need to consider an efficient strategy to transfer the advanced technology and new knowledge from overseas to domestic R&D, such as an advanced patent system, encouragement of foreign direct investment (FDI), and international cooperation for technology development. In addition, as the government R&D investment has outweighed private R&D since 2010, policy makers should impose complementary instruments to lead private R&D, such as an R&D investment tax credit, R&D investment loans with low interest, and so on.

As the second suggestion, the various policies for market expansion should be harmonized and implemented consistently. In the dynamics of market-pull policies, a price-based policy can be regarded as a long-term sustainable solution for the development as well as installation of technology, and policy makers should consider them an important instrument in the harmonization of support schemes.

Further, the estimation results show that it is necessary to impose policy instruments that induce competition between renewable energy technologies and between the broader and more advanced technologies within them, as the renewable energy technologies develop more and more. In solar PV, the renewable energy obligations are directly significant for increasing domestic innovation and leading to greater export flows. Therefore, this policy can be implemented as per a long-term schedule and with quotas specified for each technology.

Comparing the environmental policy with the renewable energy policy, environmental policies such as environmental taxes can be considered a new instrument to stimulate the innovation of highly developed renewable energy technologies, complementing the renewable energy policy. In case technological innovations and cost reduction are lax in the highly cost-competitive technology, environmental policies may promote fresh competition in energy resources, which might enable wind power to reduce costs and improve foreign competitiveness.

In short, the technology selective instruments including technology-push and price-based policies play a significant role in an economy's sustainable growth, and competition-inducing instruments including the renewable energy obligations and environmental taxes need to be imposed to avoid innovation sloth. In other words, this implies that technological progress requires more competition in the domestic and global markets, supporting the Darwinian effect[27].

On the basis of its empirical results and the foregoing implications, this thesis emphasizes a harmonization strategy as follows: the instruments for a technology-push strategy, such as public R&D and tariff incentives, should be imposed for both solar PV and wind power. Using technology, policy makers can introduce different competition-inducing instruments, for example, renewable energy obligations for solar PV and environmental taxes for wind power. In case technologies are more competitive and utilities' right to choose a clean energy technology is strengthened further, it would be necessary to consider a competition system using technology. In other words, renewable energy obligations need to be complemented, specifying a quota by technology, because environmental taxes have not been positive on the sustainable growth of solar PV until now. This thesis would therefore emphasize that the target of policies should be adjusted

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[27] The Darwinian effect indicates that more competition motivates firms to invest in R&D. For more details, see Calderini and Garrone (2001).

by technology, and the policies should be diversified for the symmetric development of renewable energy technologies.

Although this thesis has several limitations and needs to be further refined, it would help future studies to investigate empirically the progress of technology for sustainable economic growth at the national level.

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Appendix 1: The decomposition result by time division

A.1. Empirical result of OECD

[1] The change of CO_2 emissions and the effects of contributing factors in OECD countries, 1990-1998

Country	D_{TOT}	D_{EMXEF}	D_{PEIEF}	D_{STREF}	D_{EATEF}	D_{EUEEF}	D_{ESTEF}
Australia	1.1702	0.9951	1.0000	0.8970	1.3057	0.9996	1.0043
Austria	1.1864	0.9841	1.0068	0.9802	1.1952	1.0042	1.0179
Belgium	1.2188	0.9760	1.0641	0.9768	1.1674	1.0128	1.0162
Canada	1.0923	1.0038	0.8943	1.0091	1.2165	0.9727	1.0190
Czech	0.4830	0.8833	0.4955	0.8880	1.1135	1.1092	1.0061
Denmark	0.9506	0.9689	-	1.0293	1.1900	0.9790	-
France	1.0404	0.9673	0.8944	1.0146	1.1659	0.9926	1.0242
Germany	0.6845	0.8905	0.6653	0.9162	1.1781	1.0366	1.0326
Greece	1.0587	0.9758	1.0118	0.9082	1.1512	1.0230	1.0027
Hungary	0.6661	0.9578	0.6727	0.9866	1.0214	1.0081	1.0176
Ireland	1.0742	0.9622	0.6889	1.0237	1.6031	0.9600	1.0287
Italy	0.9973	0.9690	0.9114	0.9994	1.1073	0.9998	1.0205
Japan	0.9470	0.9785	0.9065	0.9215	1.1499	0.9826	1.0254
Korea	1.5110	1.0062	1.0172	1.0137	1.4679	0.9652	1.0279
Mexico	1.0543	1.0030	0.7872	1.0701	1.2602	0.9852	1.0050

Netherlands	0.9816	0.9871	0.8364	0.9547	1.2494	0.9755	1.0217
New Zealand	0.9314	0.9841	0.8215	0.9598	1.2006	0.9891	1.0109
Norway	1.2048	1.0230	1.0374	0.9073	1.2889	0.9628	1.0082
Poland	1.2488	0.9957	0.5597	1.0950	2.0707	0.9797	1.0086
Portugal	1.2357	0.9660	1.0731	0.9559	1.1939	1.0409	1.0035
Slovakia	0.4856	0.9146	0.3976	1.0777	1.1486	1.0587	1.0190
Spain	1.0687	0.9237	0.9749	0.9917	1.1035	1.0713	1.0123
Sweden	1.1548	0.9823	-	1.1449	1.2052	0.9875	-
Switzerland	0.9599	0.9525	-	1.0023	1.0608	0.9921	-
United Kingdom	0.9206	0.9235	0.8487	0.9394	1.1774	1.0335	1.0276
United States	0.8334	0.9329	0.6683	1.0053	1.2898	1.0094	1.0214
Geometric mean[a]	0.9749	0.9650	0.8117	0.9853	1.2285	1.0044	1.0165

[a] Denmark, Sweden and Switzerland in infeasible LP problems are excluded in the calculation of geometric mean.

[2] The change of CO_2 emissions and the effects of contributing factors in OECD countries, 1998-2006

Country	D_{TOT}	D_{EMXEF}	D_{PEIEF}	D_{STREF}	D_{EATEF}	D_{EUEEF}	D_{ESTEF}
Australia	1.0981	0.9689	0.9999	0.8681	1.2690	1.0323	0.9966
Austria	1.1698	1.0013	0.9316	1.0566	1.2001	0.9996	0.9894
Belgium	0.8577	0.9458	0.7837	0.9456	1.1753	1.0433	0.9979
Canada	1.1820	1.0149	0.9758	0.9398	1.2912	0.9866	0.9970
Czech	0.8825	1.0133	0.5180	1.1881	1.4432	0.9709	1.0099
Denmark	0.9422	0.9985	-	0.9693	1.1357	1.0158	-

France	0.8999	1.0063	0.8115	0.9865	1.1596	0.9762	0.9868
Germany	0.8971	0.9874	0.7968	1.0202	1.1457	0.9870	0.9885
Greece	0.9640	0.9495	0.7844	1.0051	1.2412	1.0419	0.9956
Hungary	0.9476	1.0158	0.6389	1.0321	1.4597	0.9710	0.9981
Ireland	1.1946	0.9987	0.9376	0.8067	1.5751	1.0175	0.9867
Italy	1.0713	1.0078	1.0617	0.9273	1.0779	1.0196	0.9825
Japan	1.0555	0.9921	0.9213	1.0241	1.1308	1.0067	0.9906
Korea	0.8700	0.9739	0.5125	1.0994	1.6042	0.9948	0.9935
Mexico	0.8271	0.9792	0.7136	0.9567	1.2385	1.0016	0.9974
Netherlands	0.9528	1.0026	0.8372	0.9759	1.1840	0.9850	0.9975
New Zealand	1.1704	1.0060	0.9379	0.9775	1.2823	0.9939	0.9957
Norway	0.8843	0.9472	0.7745	0.9118	1.2811	1.0451	0.9874
Poland	0.7798	0.9446	0.5515	0.9830	1.5011	1.0144	1.0000
Portugal	0.8654	0.9518	0.8209	0.9464	1.1187	1.0495	0.9968
Slovakia	0.8218	0.9942	0.4808	1.1900	1.4528	0.9908	1.0037
Spain	1.2496	0.9529	0.9678	0.9394	1.3813	1.0573	0.9876
Sweden	0.7521	1.0116	-	1.0798	1.3286	0.9253	-
Switzerland	1.0726	1.0002	-	1.0134	1.1333	0.9903	-
United Kingdom	0.8443	0.9863	0.8041	0.8682	1.2462	0.9970	0.9869
United States	1.0763	1.0369	0.8777	0.9804	1.2663	0.9579	0.9943
Geometric mean[a]	0.9643	0.9877	0.7832	0.9845	1.2739	1.0023	0.9939

[a] Denmark, Sweden and Switzerland in infeasible LP problems are excluded in the calculation of geometric mean.

A.2. Empirical result of non-OECD

[1] The change of CO_2 emissions and the effect of contributing factors in non-OECD countries, 1990-1998

Country	D_{TOT}	D_{EMXEF}	D_{PEIEF}	D_{STREF}	D_{EATEF}	D_{EUEEF}	D_{ESTEF}
Argentina	1.3087	1.0082	0.8632	0.9969	1.5495	0.9610	1.0130
Bolivia	2.0299	1.0073	-	0.9997	1.3740	0.9782	-
Brazil	1.2827	0.9852	-	0.9688	1.1957	1.0156	-
Chile	1.5060	0.9597	1.0110	0.9281	1.6072	1.0384	1.0022
China	1.3048	0.9914	0.4795	1.3064	2.0884	1.0025	1.0036
Cuba	0.5181	0.9831	0.5867	1.0398	0.8505	1.0065	1.0091
Ecuador	1.2191	0.9979	-	0.9998	1.2777	0.9947	-
Guatemala	1.7929	0.9953	1.3942	0.9379	1.3516	1.0123	1.0068
India	1.1569	0.9716	0.7166	1.0333	1.5600	1.0215	1.0092
Indonesia	0.9763	0.9976	0.5984	1.1736	1.4456	0.9603	1.0038
Pakistan	1.3093	0.9661	-	0.9825	1.3762	1.0337	-
Peru	1.3268	1.0217	0.9754	1.0053	1.3523	0.9711	1.0085
Philippines	1.3379	1.0116	1.0755	1.0080	1.2055	0.9938	1.0182
South Africa	0.9434	0.9942	0.9012	0.9475	1.1072	0.9993	1.0046
Tanzania	1.2181	1.0047	0.8815	0.9923	1.3865	0.9910	1.0089
Uruguay	1.0559	0.9762	0.9407	0.9104	1.2401	1.0132	1.0052
Zimbabwe	0.7970	0.9641	0.6983	1.0024	1.1613	1.0102	1.0067
Geometric mean[a]	1.1900	0.9902	0.8827	1.0099	1.3376	0.9999	1.0080

[a] Bolivia, Brazil, Ecuador and Pakistan in infeasible LP problems are excluded in the calculation of geometric mean.

[2] The change of CO_2 emissions and the effect of contributing factors in non-OECD countries, 1998-2006

Country	D_{TOT}	D_{EMXEF}	D_{PEIEF}	D_{STREF}	D_{EATEF}	D_{EUEEF}	D_{ESTEF}
Argentina	1.0787	0.9762	0.9708	1.0160	1.0974	1.0269	0.9940
Bolivia	1.4128	1.0108	-	1.0241	1.2433	0.9835	-
Brazil	1.3205	0.9931	-	0.9782	1.2644	1.0109	-
Chile	1.3386	0.9559	1.0233	0.9753	1.3365	1.0392	1.0103
China	1.2918	0.9798	0.6301	1.0726	1.9224	1.0074	1.0073
Cuba	0.6952	0.8931	0.6608	0.6530	1.6218	1.1034	1.0081
Ecuador	0.7813	0.9697	-	0.6985	1.0979	1.0278	-
Guatemala	1.2484	1.0022	1.0465	0.9732	1.2395	0.9857	1.0011
India	1.2039	0.9909	0.6978	1.0604	1.6264	0.9991	1.0104
Indonesia	2.2081	1.0819	1.4630	1.0266	1.4047	0.9653	1.0022
Pakistan	1.5694	0.9924	-	1.1994	1.5970	0.9965	-
Peru	1.0907	0.9703	0.7809	1.0451	1.3611	1.0129	0.9990
Philippines	1.0731	1.0228	0.7657	0.9794	1.4341	0.9744	1.0013
South Africa	0.9576	0.9721	0.7339	0.9570	1.3655	1.0193	1.0076
Tanzania	1.4422	1.0074	0.9059	1.0355	1.5298	0.9884	1.0093
Uruguay	0.8971	0.9883	0.8150	1.0720	1.0393	1.0019	0.9979
Zimbabwe	0.6947	1.0051	1.1063	0.9154	0.6822	0.9922	1.0083
Geometric mean[a]	1.1445	0.9883	0.8964	0.9717	1.3136	1.0075	1.0046

[a] Bolivia, Brazil, Ecuador and Pakistan in infeasible LP problems are excluded in the calculation of geometric mean.

Appendix 2: Model comparison for robustness in solar PV

Model 1: Domestic endogenous technological change system using simultaneous equations, i.e., Eq.(3-6), (3-9), and (3-14)

Model 2: R&D activity and international trade using simultaneous equations, i.e., Eq.(4-1), (4-3), and (4-4)

Model 3: Sustainable innovation system with international trade using simultaneous equations, i.e., Eq. (3-9), (3-14), (4-1), (4-3), and (4-4)

[1] Result of invention in solar PV

	Model 1	Model 2	Model 3
Explanatory variables			
Export	-	-0.080	-0.178
		(0.589)	(0.477)
Import	-	-0.011	-0.250
		(0.955)	(0.353)
Cumulative capacity	0.210***	0.215***	0.381*
	(0.013)	(0.004)	(0.098)
Domestic knowledge stock (t-1)	-0.048	0.116	-0.017
	(0.633)	(0.162)	(0.898)
Overseas knowledge stock (t-1)	0.221**	0.228**	0.155
	(0.037)	(0.039)	(0.421)
Policy variables			
Public R&D	0.164**	0.083*	0.218**

	(0.048)	(0.097)	(0.013)
Tariff incentives	0.376**	0.365**	0.360**
	(0.019)	(0.018)	(0.043)
Renewables obligations	0.212	0.068	0.346**
	(0.212)	(0.628)	(0.031)
Environmental taxes	0.136	-0.233	-0.199
	(0.477)	(0.120)	(0.367)
Public investment	-0.284**	-0.212	-0.225
	(0.017)	(0.132)	(0.197)
Control variables			
Science resources	-0.284	-	0.452
	(0.437)		(0.637)
Population	-	-0.454***	-
		(0.002)	
Constant	-8.164***	0.994	-1.769
	(0.000)	(0.637)	(0.547)
R^2	0.683	0.652	0.725
Learning-by-using rate	0.135	0.138	0.232

Note: The number in parentheses refers to p-value and asterisks indicate statistical significance, i.e., * p<0.1, ** p<0.05 and *** p<0.01.

[2] Results of the innovation in solar PV

	Model 1	Model 3
Explanatory variables		
Cumulative capacity	-0.199***	-0.210***
	(0.000)	(0.000)
Domestic knowledge stock (t)	-0.103***	-0.098***
	(0.001)	(0.007)

Overseas knowledge stock (t)	0.002	-0.026
	(0.937)	(0.424)
Absorption capacity	-0.015	0.028
	(0.509)	(0.708)
Policy variables		
Tariff incentives	0.072	0.112*
	(0.241)	(0.097)
Renewables obligations	-0.132**	-0.127**
	(0.035)	(0.044)
Environmental taxes	-0.116*	-0.111
	(0.091)	(0.110)
Public investment	-0.229***	-0.202***
	(0.000)	(0.000)
Control variables		
Raw material prices	0.135***	0.178***
	(0.000)	(0.000)
Gross domestic product	0.353***	0.335***
	(0.000)	(0.000)
Constant	4.771***	4.992***
	(0.000)	(0.000)
R^2	0.801	0.800
Learning-by-doing rate	0.129	0.135
Learning-by-searching rate	0.069	0.066

Note: The number in parentheses refers to a p-value and asterisks indicate statistical significance: * p<0.1, ** p<0.05, and *** p<0.01.

[3] Results of the diffusion in solar PV

	Model 1	Model 3
Explanatory variables		

System cost	-3.826***	-3.300***
	(0.000)	(0.000)
Policy variables		
Tariff incentives	0.566**	0.942***
	(0.022)	(0.001)
Renewables obligations	-0.511	-0.326
	(0.105)	(0.275)
Environmental taxes	-0.761**	-0.686**
	(0.023)	(0.026)
Public investment	-0.999***	-0.586**
	(0.000)	(0.041)
Control variables		
Fossil fuel prices	1.968***	1.983***
	(0.001)	(0.000)
Electricity generation	1.376***	1.238***
	(0.000)	(0.000)
Constant	14.077***	10.403**
	(0.002)	(0.016)
R^2	0.786	0.819

Note: The number in parentheses refers to a p-value and asterisks indicate statistical significance: * p<0.1, ** p<0.05, and *** p<0.01.

[4] Result of import in solar PV

	Model 2	Model 3
Explanatory variables		
Cumulative capacity	0.379***	0.427***
	(0.000)	(0.000)
Domestic knowledge stock	-0.126***	-0.178*
	(0.000)	(0.077)
Policy variables		

Tariff incentives	0.041	0.232
	(0.702)	(0.138)
Renewables obligations	0.188**	0.463***
	(0.028)	(0.001)
Environmental taxes	-0.050	-0.256
	(0.577)	(0.109)
Public investment	0.039	0.302**
	(0.724)	(0.013)
Control variables		
Fossil fuel prices	1.693***	0.851***
	(0.000)	(0.000)
Electricity production	0.655***	0.565***
	(0.000)	(0.000)
Constant	3.462***	7.118***
	(0.001)	(0.000)
R^2	0.928	0.917

Note: The number in parentheses refers to p-value and asterisks indicate statistical significance, i.e., * p<0.1, ** p<0.05 and *** p<0.01.

[5] Result of export in solar PV

	Model 2	Model 3
Explanatory variables		
Cumulative capacity	0.292***	-0.042
	(0.000)	(0.748)
Domestic knowledge stock	0.459***	0.429***
	(0.000)	(0.006)
Policy variables		
Tariff incentives	0.122	-0.006
	(0.529)	(0.978)
Renewables obligations	0.713***	0.672***

	(0.000)	(0.003)
Environmental taxes	0.212	-0.511**
	(0.192)	(0.037)
Public investment	0.114	0.543***
	(0.569)	(0.005)
Control variables		
Gross domestic products	0.031	0.385**
	(0.779)	(0.014)
Gross foreign products	0.094	0.227***
	(0.228)	(0.006)
Constant	13.902***	7.955***
	(0.000)	(0.003)
R^2	0.837	0.836

Note: The number in parentheses refers to p-value and asterisks indicate statistical significance, i.e., * p<0.1, ** p<0.05 and *** p<0.01.

Appendix 3: Model comparison for robustness in wind power

Model 1: Domestic endogenous technological change system using simultaneous equations, i.e., Eq.(3-6), (3-9), and (3-14)

Model 2: R&D activity and international trade using simultaneous equations, i.e., Eq.(4-1), (4-3), and (4-4)

Model 3: Sustainable innovation system with international trade using simultaneous equations, i.e., Eq. (3-9), (3-14), (4-1), (4-3), and (4-4)

[1] Result of invention in wind power

	Model 1	Model 2	Model 3
Explanatory variables			
Export	-	0.125*	-0.241
		(0.054)	(0.145)
Import	-	-0.180*	-0.104**
		(0.069)	(0.012)
Cumulative capacity	0.521**	0.210**	1.125***
	(0.019)	(0.028)	(0.006)
Domestic knowledge stock (t-1)	-0.417	0.073	-0.606**
	(0.116)	(0.598)	(0.029)
Overseas knowledge stock (t-1)	0.534**	0.334***	0.123
	(0.013)	(0.005)	(0.712)
Policy variables			
Public R&D	0.231*	0.177**	0.346***

	(0.088)	(0.046)	(0.001)
Tariff incentives	0.688**	0.381*	0.779*
	(0.013)	(0.079)	(0.082)
Renewables obligations	-0.763**	-0.201	-0.169
	(0.016)	(0.378)	(0.573)
Environmental taxes	0.006	-0.560***	2.655
	(0.981)	(0.005)	(0.104)
Public investment	-0.636*	0.050	-0.233
	(0.096)	(0.851)	(0.719)
Control variables			
Science resources	0.089	-	2.376**
	(0.886)		(0.049)
Population	-	-0.362**	-
		(0.036)	
Constant	-12.204***	-2.547	-13.694***
	(0.000)	(0.369)	(0.000)
R^2	0.712	0.597	0.861
Learning-by-using rate	0.303	0.135	0.542

Note: The number in parentheses refers to p-value and asterisks indicate statistical significance, i.e., * p<0.1, ** p<0.05 and *** p<0.01.

[2] Result of the innovation in wind power

	Model 1	Model 3
Explanatory variables		
Cumulative capacity	-0.091**	-0.084***
	(0.011)	(0.000)
Domestic knowledge stock (t)	-0.089*	-0.095**
	(0.098)	(0.028)
Overseas knowledge stock (t)	-0.023	0.026
	(0.592)	(0.408)

Absorption capacity	0.088	-0.649***
	(0.410)	(0.000)
Policy variables		
Tariff incentives	-0.056	0.149**
	(0.373)	(0.012)
Renewables obligations	0.043	0.062
	(0.530)	(0.189)
Environmental taxes	-0.219***	-0.236**
	(0.001)	(0.013)
Public investment	0.262***	0.114*
	(0.002)	(0.074)
Control variables		
Raw material prices	0.328***	0.308***
	(0.000)	(0.000)
Gross domestic product	0.094	1.297***
	(0.222)	(0.000)
Constant	4.731***	-12.326***
	(0.000)	(0.143)
R^2	0.770	0.893
Learning-by-doing rate	0.061	0.057
Learning-by-searching rate	0.060	0.064

Note: The number in parentheses refers to a p-value and asterisks indicate statistical significance: * p<0.1, ** p<0.05, and *** p<0.01.

[3] Result of the diffusion in wind power

	Model 1	Model 3
Explanatory variables		
System cost	-4.376***	-2.655***
	(0.000)	(0.000)
Policy variables		

Tariff incentives	0.173	0.813**
	(0.548)	(0.040)
Renewables obligations	0.594*	0.662**
	(0.050)	(0.014)
Environmental taxes	-0.768**	-0.516
	(0.028)	(0.370)
Public investment	0.842**	0.793**
	(0.018)	(0.039)
Control variables		
Fossil fuel prices	5.024***	4.793***
	(0.000)	(0.000)
Electricity generation	0.176	-0.075
	(0.300)	(0.856)
Constant	17.179***	8.966*
	(0.000)	(0.060)
R^2	0.858	0.905

Note: The number in parentheses refers to a p-value and asterisks indicate statistical significance: * p<0.1, ** p<0.05, and *** p<0.01.

[4] Result of import in wind power

	Model 1	Model 3
Explanatory variables		
Cumulative capacity	0.330**	1.171**
	(0.038)	(0.045)
Domestic knowledge stock	0.297	-3.909***
	(0.253)	(0.000)
Policy variables		
Tariff incentives	0.987*	2.782*
	(0.079)	(0.091)
Renewables obligations	0.073	2.340*

	(0.897)	(0.060)
Environmental taxes	0.047	1.470
	(0.931)	(0.533)
Public investment	0.366	5.672***
	(0.591)	(0.001)
Control variables		
Fossil fuel prices	2.440**	5.765
	(0.012)	(0.118)
Electricity production	1.617***	10.460***
	(0.000)	(0.000)
Constant	-17.116***	-156.589***
	(0.009)	(0.000)
R^2	0.636	0.727

Note: The number in parentheses refers to p-value and asterisks indicate statistical significance, i.e., * p<0.1, ** p<0.05 and *** p<0.01.

[5] Result of export in wind power

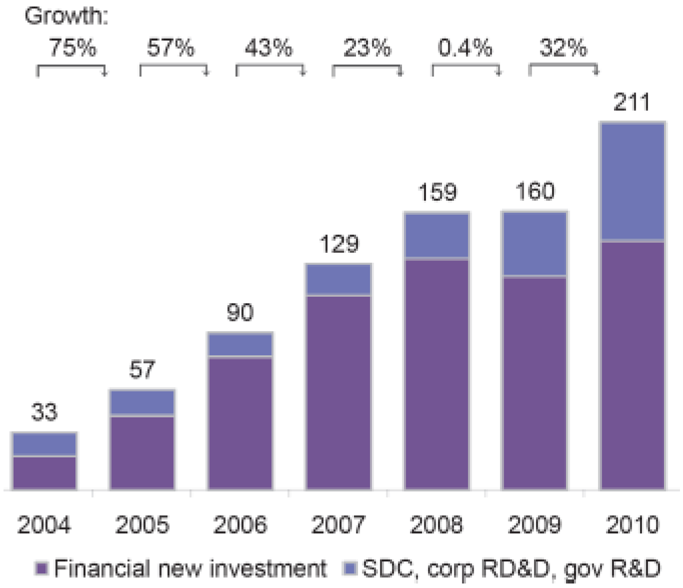
	Model 1	Model 3
Explanatory variables		
Cumulative capacity	1.072***	2.090***
	(0.000)	(0.000)
Domestic knowledge stock	0.838***	-0.788
	(0.003)	(0.318)
Policy variables		
Tariff incentives	0.057	1.903
	(0.925)	(0.103)
Renewables obligations	-1.543**	-0.885
	(0.014)	(0.332)
Environmental taxes	-0.382	8.469***
	(0.495)	(0.000)

Public investment	-2.055***	-1.581
	(0.001)	(0.203)
Control variables		
Gross domestic products	-0.555	3.504**
	(0.245)	(0.045)
Gross foreign products	-2.727	-4.251
	(0.380)	(0.564)
Constant	60.944	23.751
	(0.274)	(0.866)
R^2	0.687	0.836

Note: The number in parentheses refers to p-value and asterisks indicate statistical significance, i.e., * p<0.1, ** p<0.05 and *** p<0.01.

Appendix 4: The trend of technology and market in renewable energy since mid-2000

Since mid-2000, clean energy technologies show remarkable growth despite global financing crisis and European fiscal deficit. In technological deployment, average annual growth rate of energy efficiency technology is 1.3% during 2005-2008, that of wind power shows 27% during 2005-2010 and solar PV experienced the highest growth as 60% during 2004-2009 (IEA, 2011a). Especially, renewables technologies have been invested steeply except 2009, and wind farms for China and small-scale solar PV market for Europe raise new investment as 32% up on the level of 2009 (UNEP/BNEF, 2011).

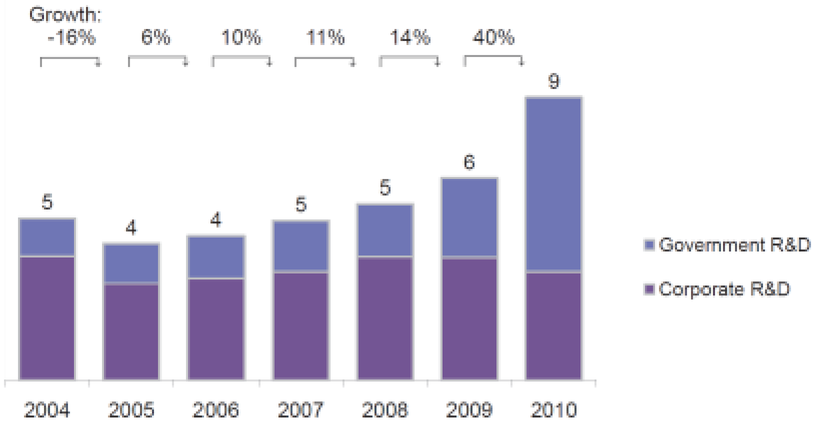


[1] Global new investment in renewable energy, 2004-2010

Source: Bloomberg New Energy Finance, 2011

The major characteristics of recent market are intensified competition by new entry of developing countries including China and India, and Asia becomes growth-oriented by low investment in Europe while aggressive investment in Asia. In solar PV, Asia has experienced increase in market share by increased demand in China and Japan. In wind power, China also raises its market share, adding huge capacity that reaches 50% of new installed capacity in the world. Whereas, Europe and North America reduce their investment due to economic recession and increased wind power cost by higher raw material price and lack of components (IEA, 2011a).

In terms of R&D investment on innovation, as the world recognized green growth as a new growth engine during the financial crisis, world R&D investment to renewable energy in 2010 reaches 90 billion USD with 40% up compared to 2009. However, government R&D increases instead private R&D shrinks, which government investment outweighs private investment at the first time (UNEP/BNEF, 2011). Solar PV has the largest share of R&D investment as 40% due to its large potential for technological innovation and market expansion. Wind power has smaller share than solar PV as 14.4%.



[2] Increase in government R&D investment

Source: Bloomberg New Energy Finance, 2011

Policy trend shows that a mixed support system tends to help technological development and market growth rather than a single policy despite national variation. Denmark introduced FIT in 1996 and complemented the policy with RPS in 1998, which results in large development of wind power (IEA, 2009e). Germany imposed FIT since 1991 and has continued to implement the support policy consistently, which results in the largest solar PV market in the world. China introduces hybrid support system that consists of RPS, FIT and tender for rapid development of renewable energy and as a result, this system seems to be successful because China experiences the fastest growth of renewable energy (IEA, 2011d).

Abstract (Korean)

전세계적으로 청정에너지기술에 대한 투자는 최근 가파르게 증가하고 있는 추세이다. 그럼에도 불구하고 이 분야의 민간 R&D 투자는 사회적 최적수준에 미치지 못하는 시장실패가 나타나는데 그 원인에는 크게 환경적 외부성(온실가스배출에 대한 제약 또는 가격 책정의 미비)과 지식외부성(공공재적 지식특성에 의한 free-riding)에 기인한다. 이 같은 외부성을 해결하고 청정에너지기술의 국가적 혁신을 달성하기 위해 정부는 다양한 기술공급 정책과 시장수요 확대정책을 시행하고 있다. 본 논문의 목표는 이 같은 일련의 사회현상을 다양한 모델기법에 의한 실증연구를 통해 규명하고 혁신, 확산, 그리고 정부정책이 청정에너지기술의 지속 가능한 성장에 미치는 영향력을 평가하는데 있다. 연구는 크게 세 부분으로 이루어지는데,

첫째, 청정에너지기술의 확산 특성을 전세계적으로 살펴보고 그 과정에서 발생하는 현상을 실증적으로 분석한다. 즉, 세계 다수의 국가(약 43개국)를 대상으로 에너지절약기술의 효율성 역설 현상을 비모수적 기법으로 모델링하여 분석하는 것이다. 구체적으로, 국가별 CO_2배출 요인을 분석하되 생산성기반의 요인분해분석 방법을 독자적으로 개발하여 기술효율성 변화와 기술혁신변화의 영향성까지 파악함으로써 에너지절약기술의 시장실패로 나타나는 energy efficiency paradox phenomenon(에너지효율적인 기술이 있음에도 확산이 제대로 이루어지지 않는 현상)을 정량적으로 파악한다. 분석결과, 국가 마다 에너지절

약 기술의 효율과 혁신역량의 편차가 있으나 전반적으로 북유럽, 서유럽, 북미, 한국, 일본 등이 타 지역에 비해 시장실패효과가 덜한 것으로 나타났으며 교토협약이 체결된 1998년 이후 다수의 OECD국가들이 대외 기술을 흡수하는 역량을 강화하는 것으로 나타났다. 또한, 효율성역설현상에 관한 다각적인 분석을 위해 온실가스저감 잠재력을 국가간 횡단면(cross-section) 비교를 통해 살펴본 결과 OECD 및 Non-OECD의 다수국가의 저감잠재력은 시간이 지남에 따라 감소하며 이는 역으로 보면, 온실가스 저감을 위해 노력하고 있음을 말한다. 그러나 잠재력자체는 Non-OECD 국가들이 더 크게 나옴으로써 이들 국가에서 효율적 기술이 더 많이 확산될 필요가 있음을 알 수 있다.

이 같은 분석을 통해 청정에너지의 기술확산은 시장경쟁에 의해 자연적으로 이루어지는 것이 아니라 여러 경제환경, 기술적 요인과 더불어 국제 규범과 각 국가의 정책적 지원이 동반될 때 제대로 이루어 질 수 있음을 확인하였다.

두 번째 연구로서, 정부의 정책적 지원이 필요한 청정에너지기술에서 정책의 효율적인 전략을 수립하기 위해서는 정책의 영향력을 다각도로 평가해 볼 필요가 있다. 이에 본 논문은 OECD국가들의 재생에너지기술을 대상으로 슘페터 이론에 기반한 "발명-혁신-확산"의 3단계로 구성되는 국내 혁신시스템을 모델링하고 혁신시스템 내의 상호작용과 정책의 영향력을 실증적으로 분석한다. 분석은 태양광과 풍력 기술에 대하여 1991~2007년까지 OECD국가들을 대상으로 패널분석을 실시하였다. 정부의 다양한 재생에너지 확대정책을 크게 다섯 가지로 분류하여(Public R&D, Tariff incentives, Renewables obligations, Environmental taxes, Public investment) 혁신시스템의 각 단계에 미치는 정태적 영향력을 파악한다. 정책의 정태적 영향력은 혁신시스템 내의 상호작용을 통제한 후 평가한 것으로 정책이 발명, 혁신, 확산 단계에 독립적으로 미치는 영향력이므로 정책의 정확한 평가가 가능하다.

또한, 혁신시스템이 선순환관계 형성시 나타날 수 있는 정책들의 동태적 영향력을 시뮬레이션을 통해 분석함으로써 각 단계별 상호작용에 의한 정책의 효과를 파악할 수 있다. 분석결과, 발명-혁신-확산 간에는 선순환 작용이 발생하며, 재생에너지 기술에 따라 정책의 정태적 영향력이 달라짐을 확인하였다. 특히, Public R&D는 혁신의 동기 지원책으로서 중요한 역할을 하고 있음을 밝혔다. 동태적 영향력에서는 Public R&D와 Tariff incentives가 혁신시스템 전 단계에 긍정적인 영향을 미치고 재생에너지의 기술이 성숙할 수록 경쟁을 유도하는 정책이 혁신에 중요한 역할을 한다는 것을 확인하였다 (Environmental taxes의 경우 재생에너지내에서 가격경쟁력이 높은 풍력의 경우 혁신에 긍정적으로 작용하는 것으로 나타남).

셋째, 재생에너지기술이 환경문제해결을 위한 국내보급에 그치는 것이 아니라 국제무역을 통한 지속가능한 경제발전의 원동력으로 거듭나는 것이 주요 목표이므로 국내 혁신과 국제무역간의 상호관계를 파악하고 국제무역에 정책이 미치는 영향력을 평가하는 것이 중요하다. 따라서, 국내 혁신체계와 수출, 수입간의 상호작용 모델을 구축하고 위에서 열거된 재생에너지 정책이 수출, 수입에는 어떠한 효과를 나타내는지를 파악한다. 분석결과, 기술성숙도가 높을 수록 대외무역의 영향을 많이 받으며 기술성숙도가 높은 기술은 시장확대 및

기술확산을 통해 대외수출량을 증가시키고 R&D활동은 수입을 대체하는 것으로 나타났다. 반면, 기술성숙도가 낮은 기술은 국내 R&D를 통해 비용감소에 주력하며 이는 대외수출량에 긍정적인 영향을 미치는 것으로 파악되었다. 정책의 영향력은 태양광의 경우 경쟁을 유도하는 Renewables obligations 정책이 무역량 증가에 긍정적인 반면, 풍력의 경우 환경정책이 국내혁신과 더불어 대외경쟁력에도 긍정적이었다.

이 같은 실증분석을 바탕으로 이끌어 낼 수 있는 정책적 함의로 본 연구에서는 다음과 같은 함의를 제한하고자 한다. 우선, 시장의 경쟁심화로 기술의 경쟁력을 향상시킬 수 있도록 해야 할 것이다. 본 연구의 분석결과 태양광은 기술발전 잠재력이 높고 비용감소 여력이 크기 때문에 R&D활동을 통해 수출을 늘리고 수입을 줄일 수 있는 것으로 나타났다. 따라서, 경쟁력 향상을 위해 R&D에 대한 정부투자를 늘리되 위축된 민간 R&D를 늘릴 수 있도록 이 부분에 대한 보완이 이루어져야 한다. 풍력은 기술개발 단계가 어느 정도 완숙하고, 비용감소 잠재력이 태양광에 비해 떨어지지만 앞서 살펴보았듯이 태양광에 비해 적은 R&D투자가 이루어지고 있으므로 풍력개발에 대한 정부 R&D투자를 더 늘리는 것이 중요한데 분석결과에서도 R&D는 수입을 대체하고 있으므로 R&D 확대를 통해 대외 경쟁력을 향상시킬 수 있다.

또한, 재생에너지는 전 세계적으로 시장이 완숙하지 않으므로 일관되고 다양한 시장확대 정책이 추진되어야 하고 그 중에서도 특히 경쟁유도 정책이 국내 기술혁신과 대외경쟁력 향상을 통해 지속적인 성장을 위해 중요한 역할을 할 수 있음이 입증되었다. 태양광의 경우 renewables obligations 정책은 경쟁유

도를 통해 태양광의 비용감소와 수출에 직접적인 효과가 있으므로 할당량에 대한 장기비전을 제시하면서 도입되어야 할 것이다. 반면, 비용경쟁력이 있는 풍력의 경우 environmental taxes가 비용을 더 감소시키고 수출을 증가시킬 수 있는 정책이므로 재생에너지 확대를 위해서는 도입이 되어야 한다. 다만, 발전사업자의 선택권이 높아지고 기술간 경쟁이 심화되기 때문에 기술간 세부적인 물량할당 및 기술성숙 단계별 경쟁체계를 동반해야 균형적인 성장이 가능함이 입증되었다. 따라서, environmental taxes는 도입하되 타 재생에너지원에 비해 비용경쟁력이 약한 태양광에는 긍정적이지 못하므로 이 부분에 대한 보완 차원에서 앞서 태양광 성장에 긍정적이었던 renewables obligations 정책을 원별 할당제로 보완하여 태양광 시장을 보존하면서도 경쟁을 할 수 있도록 해야 할 것이다.

본 연구는 기술확산을 실제로 측정하기 어려워 기존연구들이 시장실패를 실증적으로 분석하기 어려웠던 점을 새로운 요인분해분석 기법을 통해 에너지 절약기술에 대한 정황적이지만 정량적 증거를 제공함으로써 국가별 시장실패의 정도를 파악하는데 의의가 있다. 또한, 재생에너지의 국내 혁신과 지속 가능한 성장모델을 구축하고 다양한 재생에너지 확대정책의 영향력을 정태 및 동태적으로 살펴봄으로써 다양한 관점에서 정책을 평가할 수 있는 초석을 마련했다는데 의의가 있다.

주요어 : 에너지효율성역설현상, 에너지사용기술, 내생적 기술변화시스템, 재생에너지 정책, 국제 무역, 지속 가능한 성장
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