Essays on resource use, technology, and climate change

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**ESSAYS ON RESOURCE USE, TECHNOLOGY,
AND CLIMATE CHANGE**

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**ESSAYS ON RESOURCE USE, TECHNOLOGY,
AND CLIMATE CHANGE**

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Summary

This thesis consists of three self-contained essays on the topic of “resource use, technology, and climate change”. The first essay is a theoretical study from a global approach examining the effects of emissions abatement policy and energy R&D investments. The second and third essays are two empirical studies from a regional approach investigating the energy consumption, energy intensity, carbon emissions, and emission intensity in the APEC-17 countries.

The first essay aims to investigate the impacts of emissions abatement policies and energy R&D investments on economic gains, abatement costs, resource use, and climate change over the time span from 2005 to 2155 in the framework of a two-sector multiple-resource hybrid model. It analyzes three emissions abatement policies: an optimal policy, a delayed policy, and a 2 °C policy proposed by the Paris Agreement 2015, and presents the heterogeneity in the impacts of R&D investments on energy efficiency and on backstop technology. It shows that the optimal policy leads to the least abatement costs compared to the delayed policy and the 2 °C policy. The more restrictive the policy is, the more severe economic damage is caused in the short run but the more economic welfare is gained in the long run. The key impact of R&D investments on energy efficiency is that it reduces the abatement costs by improving energy efficiency while the main impact of the R&D investments on backstop energy is that it lowers the costs of the backstop technology and further accelerates the substitution between fossil fuels and the backstop energy. The backstop energy replaces the fossil fuels ten years earlier in the case with R&D investments in backstop technology than the BAU case.

The second essay aims to find the drivers for the change of energy consumption and carbon emissions in 17 APEC countries over twenty years from 1990 to 2010 using the temporal Index Decomposition Analysis (IDA). Nine developed countries and eight developing countries show different patterns of energy consumption and carbon emissions over twenty years. It also examines the impact of extreme macroeconomic events on the drivers. An economic shock appears to affect the level of energy consumption and carbon emissions through an activity effect - a slow economic growth causing low levels of energy consumption and carbon emissions, but it appears not to change the structure of energy consumption and the level of energy efficiency in the short run.

The third essay aims to analyze whether there is a convergent pattern of energy and carbon intensity in the sub-regions of the APEC and to examine the factors that affect the absolute difference in energy and carbon intensity across the APEC countries using a spatial IDA method. It seeks to answer two broadly defined questions: the trends of energy intensity and carbon intensity within and between nine developed countries and eight developing countries in the APEC region and the role of three economic cooperation organizations within the APEC region. It finds that over twenty years, nine developed countries do not show a clear trend in energy and carbon intensity, while eight developing countries show a convergent tendency in energy and carbon intensity over years mainly contributed by China. The analysis of economic cooperation shows that a strong connected regional cooperation (e.g., the ASEAN) regarding economic development and energy efficiency helps enhance the convergence of energy and carbon intensity.

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List of Acronyms

AEC: ASEAN Economic Community

AMDI: the arithmetic mean Divisia index

APAEC: ASEAN Plan of Action for Energy Cooperation

APEC: Asia-Pacific Economic Cooperation

APEC-17: 17 countries (special administrative region) in the APEC including Australia, Canada, Chile, China, Hong Kong, Indonesia, Japan, Korea, Malaysia, Mexico, New Zealand, Peru, Philippines, Singapore, Thailand, the United States, and Vietnam

APEC-EWG: Asia-Pacific Economic Cooperation Energy Working Group

APT: the ASEAN Plus Three (China, Japan, and Korea)

ASEAN: Association of Southeast Asian Nations

ASEAN-6: Indonesia, Malaysia, Philippines, Singapore, Thailand, and Vietnam

AUS: Australia

CAN: Canada

CHL: Chile

CHN: China

GHG: greenhouse gas

HKG: Hong Kong

IDA: Index Decomposition Analysis

IDN: Indonesia

IEA: International Energy Agency

ITC: induced technological change

JPN: Japan

Ktoe: thousand tonnes of oil equivalent

LMDI: the log mean Divisia index

M-LMDI: the multiplicative log mean Divisia index

MEX: Mexico

Mtoe: million tonnes of oil equivalent

MYS: Malaysia

NAAEC : North American Agreement on Environmental Cooperation

NAALC: North American Agreement on Labor Cooperation

NAFTA: North American Free Trade Agreement

NPV: net present value

NZL: New Zealand

PER: Peru

PHL: Philippines

RE: R&D investments in energy efficiency

RB: R&D investments in backstop technology

ROK: South Korea, officially the Republic of Korea

SGP: Singapore

THA: Thailand

USA: the United States

VNM: Vietnam

1 Introduction

Global warming is one of the essential challenges for sustainable development. In global greenhouse gas (GHG) emissions, the major components are energy-related carbon emissions. The energy-related carbon emissions are by-products in the process of energy transformation that converts the primary energy to the final energy services. An increasing amount of R&D expenditures is invested in various energy-related programs that aim to improve the energy efficiency and to enhance the equipment for energy production and transformation (IEA, 2016). Resource use and technological progress together affect the climate change. This dissertation intends to study on the topic of “resource use, technology, and climate change” that are three well-linked issues as demonstrated above. How does the technological progress influence the trajectory of resource use? What are the impacts of resource use and technological change on the atmospheric temperature? What are the features of energy consumption and energy-related carbon emissions over a long time span? Is there a convergent or divergent tendency in the energy and carbon intensity among the member countries in a region over years? This dissertation consists of three self-contained essays to answer the above questions. The first essay is a theoretical study from a global approach examining the effects of emission abatement policy and energy R&D investments on resource substitution, climate change, economic gains, and abatement costs. The second and third essays are two empirical studies from a regional approach investigating the energy consumption, energy intensity, carbon emissions, and emission intensity in the APEC region.

Chapter 2 intends to link emissions abatement policy to technological progress and to explore the resource substitution, climate change, economic gains, and abatement costs induced by the emissions abatement policy. Some existing studies have investigated the above issues, but a few of them consider the technological change induced by environmental

policy. As Jaffe and Palmer (1997) and Fischer *et al.* (2003) suggest, the environmental policies promote the accumulation of energy knowledge and further induce the innovation of energy transformation technology. Ignoring the induced technological change leads to a wrong estimation of the resource substitution among fossil fuels and between fossil fuels and backstop resource that has features of most energy commodity with an infinite supply¹. Also, it also leads to underestimating the economic benefits and overestimating the abatement costs induced by emissions abatement policy. This study incorporates the induced technological change into the model endogenously and explicitly identifies two types of energy R&D investments: the energy R&D investments in energy efficiency and the energy R&D investments in backstop technology. It is important to emphasize the heterogeneity of energy R&D investments (IEA, 2016). The previous energy R&D investments aim to improve the energy efficiency of the process of energy transformation while the latter energy R&D investments are to expand the backstop technology system, such as solar photovoltaic system, hence to lower the costs of backstop technology per unit. Different energy R&D investments play different roles in influencing resource substitution, economic gains, and abatement costs.

The study in Chapter 2 is a theoretical study from a global approach. It adopts a hybrid model hard linking the bottom-up model to the top-down model and incorporates two endogenous energy R&D investments into the model. This study examines four emissions abatement policies scenarios including a business as usual policy, an optimal policy, a delayed policy, and a 2 °C policy proposed by the Paris Agreement 2015. The study investigates the impacts

¹ Nordhaus, W. D. (1973). "The Allocation of Energy Resources." Brookings Papers on Economic Activity 4(3): 576. introduced the concept of backstop technology that is a new technology producing a close substitute to an exhaustible resource with an infinite supply.

of four abatement policies on the energy R&D investments, resource use sequences, atmospheric temperature, economic gains, and abatement costs induced by abatement policy.

Chapter 3 and Chapter 4 present empirical studies on energy consumption, technological change, and energy-related carbon emissions from a regional approach. These two studies are interested in 17 member countries of the Asia-Pacific Economic Cooperation (APEC) for the following reasons. First, the APEC-17 region covers nine developed countries (or special administrative region) and eight developing countries. The descriptive data show that developed countries and developing countries have different patterns of energy consumption, energy intensity, carbon emissions and emission intensity. For example, the energy consumption and energy-related carbon emissions grow more rapidly in developing countries than that in developed countries. Developed countries experience a significant reduction in energy intensity from 1990 to 2010 while the developing countries do not show this pattern. The difference between developed countries and developing countries motivates the study to investigate the pattern of energy consumption and carbon emissions in the APEC-17 region. Second, there is several regional cooperation within the APEC region including the North American Free Trade Agreement (NAFTA), the Association of Southeast Asian Nations (ASEAN), and the ASEAN Plus Three (APT) forum. Although some regional cooperation agreements overlap in membership and mandate, different regional cooperation varies in focusing points and to different extents. Some cooperation covers the aspect of energy security and energy conservation. This study intends to examine the impact of regional cooperation on the energy intensity and emission intensity. Third, under the umbrella of APEC, the APEC Energy Working Group (APEC EWG) works on strengthening the regional energy security, lowering the energy-related carbon intensity, and promoting the diversification of fuels and sources. The APEC EWG releases energy balance

tables annually covering all the member countries, which provides a good reference for the energy consumption data.

Chapter 3 intends to find the trends and the key drivers of energy consumption and energy-related carbon emissions in 17 APEC countries over the time span from 1990 to 2010 employing the temporal Index Decomposition Analysis (IDA). Most existing studies explore the drivers of energy consumption and carbon emissions from a sectoral approach or a national approach. These studies restrict their scopes within developed countries. A few of studies focus on developing countries, especially on some new emerging countries, such as China and India. Other emerging developing countries that also experience rapid economic and energy growth over the past twenty years, such as Vietnam and Indonesia, are rarely studied. Identifying the drivers of energy consumption and carbon emissions in developing countries of the APEC region helps explain the essential challenges of energy conservation and the carbon emissions reduction in developing countries, which is apparently different from the case in developed countries. The time frame of this study is from 1990 to 2010 covering the Asian financial crisis in 1997 and the global economic crisis in 2008. This study also shows the impact of the macroeconomic shock on energy consumption, energy efficiency, carbon emissions, and carbon intensity.

Chapter 4 aims to check whether there is a convergent pattern in sub-regions and to examine the factors that affect the absolute difference in energy intensity and carbon intensity across the APEC countries employing the spatial IDA method. The spatial IDA method decomposes the absolute difference between a specific country and the average level of the region in a particular year, which allows a direct comparison among countries in the region. Extending chapter 3, chapter 4 first investigates whether there is a convergent tendency in energy intensity and carbon intensity a) within developed countries, b) within developing countries, and c) between the average level of developed countries and developing countries

over years and what is the key influencing factors. It also sheds light on the question how developing countries catch up developed countries in emissions reduction. Second, Chapter 4 examines if the economic cooperation helps narrow down the gap of energy intensity and carbon intensity among member countries and if the economic cooperation promotes the energy technological diffusion. The findings point out which regional policies help enhance the convergence of energy and carbon intensity among the member countries.

Chapter 5 summarizes the thesis and discusses some potential future research related to our thesis.

2 Essay 1: Energy R&D Investments and Emissions Abatement Policy

2.1 Introduction

Global average surface temperature has experienced a fast increase since the late 19th century, which becomes one of the essential challenges for sustainable development.² Some environmental policies aim to mitigate the climate change and balance the economic development between the short run and the long run. When dealing with the long-term environmental policies, it is important to take into account the interaction between environmental policies and energy technological progress. On one hand, energy-related technological progress makes it easier to meet the environmental goals. For example, backstop technologies, such as wind, solar, and other renewable technologies, drive down carbon emissions mitigating the consequences caused by global warming. On the other hand, the environmental policies, such as carbon tax, pull up the costs of fossil fuels. The high costs of fossil fuels trigger the energy-related innovation to improve the energy efficiency and accelerate the substitution between fossil fuels and backstop technology. This study aims to link energy technological progress to the environmental policy and to investigate effects of environmental policy and technological change on the resource use pattern, climate change, economic gains and emissions abatement costs.

Although a large number of studies examine the effects of environmental policy, they still have some limitations regarding the connection of energy technological progress and emissions abatement policy. Studies incorporating energy-related technological change into a model present an resource use pattern with technological progress, but they do not

² The data is from the website of intergovernmental panel on climate change (IPCC).

explicitly identify the dynamic effects between energy technological progress and emission abatement policy (Grübler and Messner, 1998; Nordhaus, 2008). Such studies miss capturing how environmental policy accelerates the technological change in the analysis. Empirical evidence from several studies suggests that environmental policy encourages energy R&D investments that enrich the energy knowledge stocks and induce the innovation process (Jaffe and Palmer, 1997; Fischer *et al.*, 2003). Ignoring the induced technological change (ITC) by abatement policy leads to underestimating the economic gains, overestimating the abatement costs, and a faulty time of the replacement of fossil fuels by backstop energy.

Although some studies such as Popp (2004) explore the energy technological progress induced by abatement policy endogenously, they do not identify the heterogeneity of the energy R&D investments. Energy R&D investments can be categorized into the R&D aiming at efficiency improvement and the R&D focusing on the backstop technology (IEA, 2016). Two R&D investments play different roles. The R&D investments in energy efficiency put efforts on the enhancement of production, transformation, and consumption chains to deliver more energy services given the same amount of primary energy. With the increase of energy services, the output and economic welfare are improved directly by the R&D investments in energy efficiency. The R&D investments in backstop technology focus on expanding the system scale to reduce the average cost per unit backstop energy (IEA, 2013; IEA, 2014). The decline in the cost of backstop technology changes the comparative advantage among different resources and further changes the fuel type chosen by sector. As energy is one of input factors in the production, a change in energy input by substitution has an indirect impact on the economic welfare. Neglecting the heterogeneity in the impact of R&D investments on energy technology in a policy analysis misidentifies the direct channel

and the indirect channel leading to a faulty assessment of the benefit and cost induced by the abatement policies.

Existing literature seems to ignore the externality and the long residence of carbon dioxide in the atmosphere in the analysis. Energy use patterns and carbon abatement policies can be studied from a sectoral approach or an aggregate approach. Although the sectoral approach can address the energy use pattern or energy-related policies within a sector in detail, it still neglects to reflect the externality of climate change in the analysis, which calls for the mitigation with efforts and incorporation globally. The impact of carbon abatement policy can be studied in different time frames. Most existing studies limit the time frame within 20-50 years (Lutz *et al.*, 2005; Kloess and Müller, 2011). However, the carbon emissions exist in the atmosphere in a long term. The interaction between the atmospheric accumulation of carbon dioxides and energy use is dynamic but very slow. Thus, extending the time horizon to 100-150 years gives an accurate estimation of the impact of an abatement policy on the economic gains and abatement costs.

Upon identifying drawbacks of the existing studies, this study aims to improve the understanding of the possible impacts of R&D investments and carbon abatement policy on resource use pattern, economic welfare, and climate change. The contribution of this study is to develop a new hybrid model with two types of endogenous energy R&D investments to address the above concerns from global perspectives. The new model has two distinct advantages over the existing models. First, the model explicitly identifies the roles of R&D investments in energy efficiency and backstop technology and evaluates the impacts of the ITC and abatement policy on energy substitution, economic gains, and abatement costs. Second, this hybrid model embraces the merits of bottom-up models and the merits of top-down models. On one hand, the new model takes the advantage of bottom-up models with technological specifics analyzing inter-fuels substitution and how soon the backstop energy

replaces fossil fuels. On the other hand, the new model possesses the nature of top-down models that embed macroeconomic system making it possible to explore the impact of abatement policies on economic gains and abatement costs.

The hybrid model combines macroeconomic system, energy system, and carbon cycle system together in the time frame of 150 years from 2005 to 2155. This study contributes to the literature with four new findings related to energy R&D investments, inter-fuels substitution, atmospheric temperature, economic gains and abatement costs. First, the study recognizes the different roles of R&D investments in energy efficiency and backstop technology. The findings present that energy R&D investments affect not only energy substitution but also the economic gains and abatement costs induced by abatement-control policy. Second, the study explores the resource use sequences in the model with endogenous technological change. The backstop energy appears to replace the fossil fuels within 100 years. Third, the study discusses the temperature change caused by energy-related emissions in different policy scenarios and shows the corresponding control rate for each scenario. Fourth, the study estimates the economic gains and abatement costs with the emission control policies incorporating two types of R&D investments endogenously. The economic enhancement is relatively small in the near term, while it becomes large in the far term. A more restrictive policy hurts the economic gains more severely in the short run but eventually benefits the economy in the long run.

The rest of the chapter is organized as follows. Section 2.2 reviews existing literature from the bottom-up approach and top-down approach. Section 2.3 and Section 2.4 demonstrate the hybrid model, data, and calibration method. Section 0 presents the results of resource use sequences, temperature change, economic gains, and abatement costs induced by the abatement policy. Section 2.6 concludes the study and makes further discussion.

2.2 Resource Use, R&D, and Climate Change: A Methodological Review

The existing studies related to the resource use and climate change are from two broadly defined approaches. They are a) the bottom-up approach with technological details of the energy system, and b) the top-down approach with energy used in production in the framework of macroeconomics. Next two sub-sections present a review of two approaches.

2.2.1 Bottom-up Approach

Bottom-up models capture the features of fuel-technology chains explicitly connecting the energy supply (the primary energy) to the energy demand (the end-use energy) through the channel of energy transformation system. A conventional bottom-up model minimizes end-use energy costs and chooses energy transformation technology with the lowest costs. These models identify different energy transformation technologies and reflect the technological progress in the energy industry.

Bottom-up models with the technological change in energy system employ two mechanisms of the technological learning process: a) learning by doing, and b) learning by researching. The ‘learning by doing’ approach shows that experience accumulation facilitates the reduction of energy costs. These models describe the learning process using a one-factor learning curve that is an exponential function of cumulative production. The representing paper concludes that the renewable energy can replace the conventional energy earlier with the ‘learning by doing’ effect (Grübler and Messner, 1998; Gritsevskiy and Nakićenović, 2000; Manne and Richels, 2004). The ‘learning by researching’ approach explicitly identifies the role of R&D investments in the technological progress of the energy system. These models present the learning-by-researching process employing a two-factor learning curve that is a function of knowledge stock and R&D investments. As the R&D expenditures

are invested in the energy-related programs, energy-related knowledge accumulates and lowers the energy costs. The representing studies show the trends of R&D investments and conclude that R&D investments explicitly accelerate the energy substitution between conventional fuels and renewable energy (Barreto and Kypreos, 2004; Miketa and Schrattenholzer, 2004).

Although bottom-up models well present the end-use technologies, they miss linking emissions abatement policy to resource substitution. First, the nature of bottom-up model leads to a lack of interaction between energy system and macroeconomic variables, such as consumption, investments, and public policies. They cannot well address the impacts of macroeconomic policy on energy substitution, emissions abatement costs, and the change of economic welfare. Second, although some studies from a bottom-up approach incorporate the environmental policy into their models, they treat the emissions abatement policy exogenously and cannot reflect the dynamic effects between policy and energy use pattern. To overcome the above drawbacks, many recent studies employ a hybrid model hard linking the bottom-up model and the top-down model to investigate the interaction between environmental policies and energy system. On one hand, taking advantages of a bottom-up model, the hybrid model can answer the questions highly relevant to the cost-effective technological options with the technological change induced by abatement policy. On the other hand, it can also address the economic gains and abatement costs overcoming the under- or no-representation of a macroeconomy in the bottom-up models.

Many studies in the framework of a hybrid model have the same goal with the studies in the framework of a bottom-up model, which aim to explore technological options in an energy system. Thus, this subsection also includes a review of such studies. Most of studies employing a hybrid model are from a sectoral approach, such as electricity generation sector and transportation sector. Hwang and Lee (2015) simulates the hypothesis scenarios under

the electricity industry reform in Korea. This study suggests that forward contracts in the liberalized electricity market effectively improve the competitiveness of electricity market. Wang *et al.* (2016) takes into account the uncontrollable variability of renewable energy and provides the substitution between renewable energy and non-renewable energy and the substitution among renewable energies. Dai *et al.* (2016) explicitly represents the curtailment and storage of variable renewable energy and estimates the energy used in the electricity generation. For the transportation sector, Jaccard *et al.* (2004) models the endogenous technological change of the personal vehicles and estimates the decision of personal vehicles given an emissions abatement policy. This study indicates that the environmental policy can get response if low-emission vehicles achieve a minimum required market share. Kloess and Müller (2011) simulates the impact of policy, energy prices, and technological progress on the passenger car in Austria. The results show that environmental policies reduce the demand for passenger car and promotes the innovation and diffusion of the technology on the efficiency improvement.

The above studies restrict their scopes of the energy system in a specific sector. The restricted scope enables capturing detailed technological features in the energy system, but these models cannot well address the dynamic effect of the energy system and environmental policies due to the environmental externality. The misidentified results lead to the wrong estimation of energy substitution, emissions abatement costs and economic gains induced by the abatement policy. A global approach is necessary especially for the model incorporating a carbon cycle system.

2.2.2 Top-down Approach

Top-down models evaluate environmental policies in the framework of macroeconomic models or general equilibrium models. The top-down model is a useful tool to analyze the effects of emissions abatement policy on energy use patterns and macroeconomic variables,

such as outputs and optimal policy of emissions abatement. Conventional top-down models are criticized due to a lack of technological flexibility in the energy system. Some studies modify the conventional top-down model to reflect the technological flexibility by introducing the policy-induced technological change.

Conventional top-down models examine the optimal policies linking the energy, economic growth, and carbon cycle together (Nordhaus, 1994; Nordhaus and Boyer, 2003; Nordhaus, 2008). The representing studies conclude that the optimal policy is the most cost-effective compared to other policy scenarios, such as the carbon concentration limit scenario and the temperature limit scenario. Buonanno *et al.* (2003) extends Nordhaus and Boyer (2003) making the technological change endogenous, examining the optimal policy under the Kyoto Protocol. The results explicitly show the international spillover effect induced by the abatement policy. Popp (2004) and Popp (2006) consider the crowd-out effect of R&D investments in the total investments and examine the economic gains and abatement costs in the framework of top-down model with an endogenous technological change. The paper concludes that the economic welfare is enhanced significantly in the model with an endogenous technological change compared to the exogenous model. Welfare gains also come from adopting the backstop technology.

The above studies analyze the technological change induced by carbon abatement policy. However, most of them simplify the energy input as one resource, which cannot address the energy substitution among multiple resources. Furthermore, their models cannot investigate the replacement of fossil fuels by the renewable energy, which is one of the key issues in the energy economics. In addition, except Popp (2006), most studies in the framework of top-down models do not identify the role of R&D investments. R&D investments can be categorized into two types: R&D investments in energy efficiency and R&D investments in the backstop energy (IEA, 2016). The previous one aims to reduce the energy intensity in

the final energy use, while the latter one is to reduce costs of backstop energy. Identifying the roles of different R&D investments is important because the R&D expenditures affect the resource use pattern and further affect the economic gains and abatement costs induced by the environmental policy.

2.3 Model

This study builds upon a hybrid model by adopting and modifying the DICE model (Nordhaus, 2008) and the ENTICE model (Popp, 2004). By developing the two models, this new model includes energy substitution among fossil fuels and between fossil fuels and backstop technology explicitly. This model contains the induced technological change (ITC) endogenously combining the bottom-up model and the top-down model to investigate the concurrent impacts of ITC on economic growth, energy use, and climate change. The model consists of an objective function, economic constraints, energy constraints, and environmental constraints. The energy conditions are keys to connect economy to environment. On one hand, energy is an input factor in the production function that affects utility function. On the other hand, energy-related emissions drive up the concentration of carbon emissions in the atmosphere, which lead to an increase in atmospheric temperature.

The model has two sectors and multiple resources to identify fuels allocation in each sector. Two sectors are the capital goods sector and the consumption goods sector. Four resources are oil products, coal products, natural gas, and backstop energy. The model endogenizes two types of ITC that aim to improve the energy efficiency and to reduce the costs of backstop technology, which shows the heterogeneity of technological change. The R&D investments affect the resource use directly. They also indirectly affect the benefits and costs induced by the abatement policy through the channel of resource use. Economic gains, abatement costs, and temperature trends are analyzed across different policy scenarios. The time frame is from 2005 to 2155 covering 150 years. The model has fifteen periods. Each

period has ten years. In the following sub-sections, the model is presented in the sequence of the objective function, economic constraints, energy constraints, and environmental constraints. Section 2.7 (Appendix) lists all equations, variables, and parameters in the model.

2.3.1 Objective Function

The objective function is to maximize the net present value of the population-weighted utility of per capita consumption over time T ($T=15$) as shown in equation (2.1). The form of objective function is a standard representation of the economic growth model. Equation (2.2) shows that the utility in each period is a function of consumption per capita.

$$\max V = \sum_{t=1}^T U_t(c_t, L_t) R_t \quad (2.1)$$

$$U_t(c_t, L_t) = L_t [c_t^{1-\alpha} / (1-\alpha)] \quad (2.2)$$

$$R_t = (1+r)^{-t} \quad (2.3)$$

In equation (2.1), c_t represents the per capita consumption. L_t is the population to reflect the labor used in production. U_t is the utility function of c_t and L_t to measure the utility of household at time t . R_t represents a social time preference discount factor (per period). In equation (2.3), r is the pure rate of social time preference (per unit time).

2.3.2 Economic Constraints

Total output is the sum of the output in two sectors: the capital goods sector and the consumption goods sector. i represents the sector type. When $i=1$, it represents the capital goods sector. When $i=2$, it represents the consumption goods sector. Three input factors,

including physical capital stock ($K_{i,t}$), labor ($L_{i,t}$), and effective energy services ($ES_{i,t}$), are used in a Cobb-Douglas production function in each sector. β_i and γ_i are the elasticity parameters of the capital stock and effective energy services respectively. In equation (2.5), other key variables are the damage function (Ω_t), the function of abatement costs (Λ_t), the energy costs ($CE_{i,t}$), and the total factor productivity (TFP, A_t). The net output takes the environmental damage and abatement costs into consideration and deducts the energy costs. The damage function is a function of atmosphere temperature (T_t), while the function of abatement costs is a function of emissions-control rate (μ_t) determined by abatement policies. The abatement costs are the function of abatement costs timing the gross output, namely, $\Lambda_t \sum_{i=1,2} A_t K_{i,t}^{\beta_i} ES_{i,t}^{\gamma_i} L_{i,t}^{1-\beta_i-\gamma_i}$. In equation (2.6) and (2.7), $a_1, a_2, \theta_1, \theta_2$ are parameters in damage function and the function of abatement costs respectively.

$$Q_t = \sum_{i=1,2} Q_{i,t} \quad (2.4)$$

$$Q_{i,t} = \Omega_t (1 - \Lambda_t) A_t K_{i,t}^{\beta_i} ES_{i,t}^{\gamma_i} L_{i,t}^{1-\beta_i-\gamma_i} - CE_{i,t}, i = 1, 2 \quad (2.5)$$

$$\Omega_t = 1 / (1 + a_1 T_t + a_2 T_t^2) \quad (2.6)$$

$$\Lambda_t = \theta_1 \mu_t^{\theta_2} \quad (2.7)$$

The increase in total physical capital stocks (K_t), including capital stocks in the capital goods sector ($K_{1,t}$) and in the consumption goods sector ($K_{2,t}$), equals to the investments in physical capital stocks at time t (I_t) minus the depreciation of capital stocks at time $t - 1$.

δ_K is the capital depreciation rate.

$$K_t = I_t + (1 - \delta_K)K_{t-1} \quad (2.8)$$

In the equilibrium, the output in the capital goods sector goes to the investments in physical capital (I_t), R&D in energy efficiency ($R_{E,t}$) and R&D in backstop technology ($R_{B,t}$). In the equilibrium, the output in consumption goods sector goes to consumption (C_t).

$$Q_{1,t} = I_t + R_{E,t} + R_{B,t} \quad (2.9)$$

$$Q_{2,t} = C_t \quad (2.10)$$

2.3.3 Energy Constraints

The effective energy services are a combination of resource ($ER_{i,t}$) and the knowledge stock of energy transformation ($H_{E,t}$). The function takes a CES form, in which ρ is the substitution ratio. To explore the energy allocation in the two sectors, the model includes four types of energy explicitly: oil products ($P_{i,t}$), coal products ($W_{i,t}$), natural gas ($G_{i,t}$), and backstop energy ($B_{i,t}$). The first three resources are fossil fuels, while the last one is renewable energy, which is assumed to have an infinite reserve. The extraction of fossil fuels are subjected to the resource reserves ($S_{J,0}, J = P, W, G$) as shown in equation (2.13).

$$ES_{i,t} = \left(ER_{i,t}^\rho + H_{E,t}^\rho \right)^{1/\rho} \quad (2.11)$$

$$ER_{i,t} = P_{i,t} + W_{i,t} + G_{i,t} + B_{i,t} \quad (2.12)$$

$$S_{J,0} \geq \sum_{t=1}^T (J_{1,t} + J_{2,t}), J = P, W, G \quad (2.13)$$

Energy costs in sector i at time t ($CE_{i,t}$) are the sum of the costs of each fuel type. The costs of fossil fuels ($z_{i,j,t}$, $j = P, W, G$) contain extraction costs and conversion costs, while the costs of backstop energy ($z_{i,B,t}$) are only conversion costs. The knowledge stock of backstop technology ($H_{B,t}$) lowers the cost of backstop energy. b is the scale parameter.

$$CE_{i,t} = z_{i,P,t}P_{i,t} + z_{i,W,t}W_{i,t} + z_{i,G,t}G_{i,t} + z_{i,B,t}B_{i,t} \quad (2.14)$$

$$z_{i,B,t} = \frac{z_{i,B,0}}{(H_{B,t})^b} \quad (2.15)$$

The model explicitly identifies two types of R&D investments: R&D investments in energy efficiency ($R_{E,t}$) and R&D investments in backstop technology ($R_{B,t}$), as well as two types of corresponding energy knowledge: knowledge stocks on energy efficiency ($H_{E,t}$) and knowledge stocks on backstop technology ($H_{B,t}$). Knowledge stocks on energy accumulate in a similar way to the physical capital stock as shown in equation (2.16). Knowledge is obsolete like physical capital as time goes by, since out-fashioned knowledge cannot generate a cutting-edged innovation any more. In period t , the knowledge creation, $h(R_{m,t-1})$, is a function of R&D investments in period $(t-1)$ and knowledge stocks in period $(t-1)$ as shown in equation (2.18). It indicates that the process of knowledge generation takes one period and that knowledge creation in period t depends on R&D investments in period $(t-1)$ and existing knowledge stocks in period $(t-1)$, which is a ‘stand on the shoulders of giants’ effect. δ_H is the depreciation rate of the knowledge stocks. m represents energy efficiency when it is E , while m stands for backstop technology when it is B . φ_1 , φ_2 , and φ_3 are parameters in the function of new knowledge stocks.

$$H_{m,t} = (1 - \delta_H)H_{m,t-1} + h(R_{m,t-1}), m = E, B \quad (2.17)$$

$$h(R_{m,t}) = \varphi_{m,1} R_{m,t}^{\varphi_{m,2}} H_{m,t}^{\varphi_{m,3}}, m = E, B \quad (2.18)$$

2.3.4 Environmental Constraints

Total carbon emissions to atmosphere (EM_t) are the sum of energy-related carbon emissions (E_t) and land-use emission as shown in equation (2.19), in which LU_0 and δ_{LU} represent the initial land-use emissions and the declining rate of land-use emissions. Equation (2.20) presents energy-related carbon emissions. μ_t is the emission-control rate induced by abatement policies. η_J ($J=P, W, G$) is emissions factor of fossil fuels (oil products, coal products, and natural gas), which quantifies the carbon emissions released to the atmosphere by burning one unit of a fossil fuel.

$$EM_t = E_t + LU_0(1 - \delta_{LU})^t \quad (2.19)$$

$$E_t = (1 - \mu_t)(\eta_P P_t + \eta_W W_t + \eta_G G_t) \quad (2.20)$$

Equation (2.21), (2.21), and (2.23) present the process of carbon dioxides exchanges among the atmosphere, shallow oceans, and lower oceans. $M_{A,t}$, $M_{U,t}$, and $M_{L,t}$ are carbon concentrations in the atmosphere, shallow oceans, and lower oceans. $\phi_{a,b}$ ($a, b=1, 2, 3$) are the parameters in the carbon-cycle equations.

$$M_{A,t} = 10 * EM_t + \phi_{33} M_{A,t-1} + \phi_{23} M_{U,t-1} \quad (2.21)$$

$$M_{U,t} = \phi_{12} M_{A,t-1} + \phi_{22} M_{U,t-1} + \phi_{33} M_{L,t-1} \quad (2.22)$$

$$M_{L,t} = \phi_{11} M_{L,t-1} + \phi_{21} M_{U,t-1} \quad (2.23)$$

The radioactive forcing (F_t) is formed by a high concentration of carbon dioxides in the atmosphere ($M_{A,t}$) and other types of greenhouse gasses, such as methane, $F_{EX,t}$. The radioactive forcing drives up the atmospheric temperature (T_t) as shown in equation (2.24) and equation (2.25). TL_t is the temperature of the lower ocean. Equation (2.25) and equation (2.26) show how the temperature in the atmosphere and the temperature in lower ocean influence each other.

$$F_t = 4.1 * [\log_2(M_{A,t} / M_{A,1750})] + F_{EX,t} \quad (2.24)$$

$$T_t = T_{t-1} + \sigma_1[F_t - \sigma_2 T_{t-1} - \sigma_3(T_{t-1} - TL_{t-1})] \quad (2.25)$$

$$TL_t = TL_{t-1} + \sigma_4(T_{t-1} - TL_{t-1}) \quad (2.26)$$

2.4 Data and Calibration

The new hybrid model uses the set of macroeconomic parameters in line with the DICE-07 model (Nordhaus, 2008) and the ENTICE-BR model (Popp, 2006) and assumes that key parameters in economy system, energy system, and environmental systems are independence. Key parameters includes the growth rate of total factor productivity, population-related parameters, the parameter of the reserves of fossil fuels, the decarbonization rate, the equilibrium temperature-sensitivity coefficients, the damage parameters, the transfer coefficient in carbon cycles.³ Existing studies (Nordhaus, 2008; Hu *et al.*, 2012) suggests that the environment-related integrated models, such as DICE model, is relatively robust in ranking policies even if the ambiguities in key parameters occur. However, the literature (Hu *et al.*, 2012; Hatase and Managi, 2015) also shows that the above

³ Nordhaus (2008) proposes key parameters to check the robustness of the DICE-07 model. This study is consistent with Nordhaus (2008).

model is sensitive to the mean values of the key parameters. This property requires the study to choose and estimate parameters carefully to give a better understanding of environmental policy as well as energy R&D investments.

This study calibrates several basic parameters in the economic constraints. Initial capital stock (K_0) and the depreciation rate of the capital stock (δ_K) are in line with the DICE-07 model. Population (L_0) and initial output (Q_0) are collected from the World Bank latest database. The growth rate of population is solved to match the growth rate indicated by the World Bank latest database and the MIT Joint Program Energy and Climate Outlook 2014. Initial total factor productivity (A_0) and the growth rate of TFP are solved to match the GDP in 2005, 2015, and 2025 that are collected from the World Bank latest database and the MIT Joint Program Energy and Climate Outlook 2014. Then, the new hybrid model has two sectors, the capital goods sector and the consumption goods sector, which is different from the DICE-07 model and the ENTICE-BR model. For each sector, elasticity factors, β_i and γ_i , are chosen to match the proportion of investment and consumption in the DICE-07 model.

For the energy constraints, the parameters related to R&D investments and knowledge stocks are calibrated. The initial knowledge stocks ($H_{E,0}$ and $H_{B,0}$) are consistent with the ENTICE-BR model. Starting values of \$1.8 billion and \$1.2 billion are chosen for the initial R&D investments at global level ($R_{E,0}$ and $R_{B,0}$). $R_{E,0}$ and $R_{B,0}$ at global level are estimated based on the proportion of energy R&D investments in the total GDP in the OECD countries provided by the IEA Energy Technology R&D Statistics (IEA, 2016).⁴ Parameter

⁴ The proportion of RE in the share of GDP is 0.0037% in 2005 and 0.0082% in 2015 in the OECD countries, while the percentage of RB in the share of GDP is 0.0031% in 2005 and 0.0081% in 2015 in the OECD countries.

$\varphi_{E,3}$ and $\varphi_{B,3}$ are taken from the ENTICE-BR model so that future elasticity falls slowly in the near future due to diminishing returns to R&D. $\varphi_{m,1}$ and $\varphi_{m,2}$ ($m=E,B$) are chosen to fit the change of R&D investments in energy efficiency and backstop technology between 2005 to 2015.

Besides the R&D investments, there are other parameters in the energy constraints. The substitution ratio between raw energy and energy efficiency (ρ) is taken from the ENTICE-BR model. The reserves of fossil fuels in 2005 are collected from BP Statistical Review of World Energy 2007 (Company, 2007). The extraction costs and conversion costs for different resources are taken from (Chakravorty *et al.*, 1997). Parameter b is chosen to meet the paths of backstop energy cost suggested by Technology Roadmap (Wind Energy, Solar Photovoltaic Energy, and Hydropower) published by IEA (IEA, 2012; IEA, 2013; IEA, 2014).

The parameters in the environmental constraints are taken from the DICE-07 model (Nordhaus, 2008) to guarantee that the environmental parameters are in line with the latest estimation.

2.5 Results

The simulation of the hybrid model presents answers to three questions: (a) what is the difference of energy substitution with and without ITC? (b) what is the impact of emissions-control policies on the climate change? (c) what is the impact of the emissions abatement policies on economics gains and abatement costs? This study simulates four policy scenarios:

- (a) A business as usual (BAU) scenario without an emission-abatement policy;
- (b) An optimal policy scenario in which the marginal cost of carbon reduction equals the marginal benefit from the emissions abatement;

- (c) A delayed policy scenario in which the carbon emission is controlled from 2035 onwards. The policy is postponed to ten years later in the delayed policy scenario compared to the optimal policy scenario;
- (d) A 2 °C policy scenario in which the atmosphere temperature is below 2 °C above pre-industrial levels, which is the goal of the Paris Agreement; here, the emission-control rate is determined optimally to maximize the objective function subject to the constraint of temperature target.

Each scenario considers four sub-models:

- i. A basic model without the induced R&D investments. The human capital of energy efficiency and the cost of backstop technology are fixed;
- ii. A model with R&D investments in energy efficiency (RE) that incorporates the induced technological change for efficiency improvement, but the cost of backstop resource is unchanged over the entire time horizon;
- iii. A model with R&D investments in backstop technology (RB) in which the induced technological change reduces the cost of backstop technology, but the human capital of energy efficiency remains fixed;
- iv. A model with R&D investments in both energy efficiency and backstop technology, in which there are two types of induced technological change that bring efficiency improvement and reduce the cost of backstop technology.

2.5.1 R&D Investments, Resource Substitution, and Climate Change

This model explicitly identifies the heterogeneity of energy R&D investments. RE is to accumulate the knowledge stock on energy efficiency (HE) and further to improve the level of final energy services in the production given the same amount of primary energy. The complementary effect between resource and energy efficiency technology makes the path of

RE positively related to the path of the resource. A high-level of resource used in production leads to a high level of R&D on energy efficiency. RB is to expand the system scale of the backstop technology and further to lower the backstop energy cost. RB changes the comparative advantage of energy costs among fossil fuels and backstop energy. Boosted by RB, backstop energy replaces fossil fuels earlier than the case without RB. ons abatement than that of RE.

Table 2.1 summarizes the paths of RE and RB in different scenarios over the entire time span. The R&D investments are in the unit of constant 2005 billion USD. The results within a panel illustrate the relationship of RE and RB as follows. The comparison of case i) and case iii) shows that RE increases faster in case iii) than that in case i), which indicates that there is a joint effect of RE and RB. The RB reduces the cost of backstop energy resulting in an increase of the quantity of resource used in each period. The complementary effect of the resource (ER) and knowledge stock on energy efficiency (HE) makes RE increase faster in case iii) to support a higher level of knowledge stock matching a larger quantity of resource supply. The comparison of case ii) and case iii) shows that RB increases more slowly in case iii) than that in case ii) indicating that the there is also a crowd-out effect between RE and RB. The increase in R&D investments in energy efficiency rules out the possible R&D investments in backstop energy.

This paragraph presents an analysis across different policy scenarios (Panel A to D). The value of RE with policy control is almost always less than that without policy. The reason is that the raw resource is constrained by the policy leading to a less RE due to the complementary effect. A more restrictive the policy is, a less RE is in each period. For RB, case ii) and case iii) are discussed separately. In case ii), control policy limits the use of fossil fuels accelerating the backstop energy to replace fossil fuels. RB in case ii) has a high level in the scenario with a more restrictive policy. In case iii), there are two methods to

increase the energy services: a) improving energy efficiency, b) reducing backstop energy costs. The results of RE and RB in case iii) indicate that the scenarios with optimal policy and with delayed policy rely more on the method a), while the scenario with 2°C policy relies more on method b). It indicates that a faster growth of RB helps achieve an ambitious goal of emissions abatement than that of RE.

Table 2.1 The Trends of R&D on Energy Efficiency and Backstop Technology (2005 Billion USD)

R&D (2005 Billion USD)		2005	2015	2025	2035	2045	2055	2065	2075	2085	2095	2105	2115	2125	2135
Panel A: BAU															
i. with RE	RE	1.80	4.07	4.68	5.33	6.23	7.28	8.37	9.29	9.67	8.94	8.17	7.17	5.70	3.75
ii. with RB	RB	1.20	6.54	9.13	12.99	19.20	28.69	42.64	62.22	64.94	64.50	63.36	59.28	50.12	34.68
iii. with	RE	1.80	4.89	5.69	6.48	7.50	8.61	9.61	10.15	9.71	9.24	8.67	7.71	6.17	4.05
RE & RB	RB	1.20	6.25	8.73	12.47	18.50	27.75	41.42	60.68	63.49	63.13	62.09	58.17	49.25	34.15
Panel B: Optimal Policy															
i. with RE	RE	1.80	4.05	4.65	5.31	6.22	7.28	8.38	9.30	9.68	8.90	8.16	7.18	5.72	3.76
ii. with RB	RB	1.20	6.64	9.27	13.20	19.52	29.20	43.44	63.40	64.75	64.56	63.57	59.57	50.40	34.88
iii. with	RE	1.80	4.88	5.67	6.47	7.48	8.59	9.60	10.12	9.68	9.24	8.68	7.74	6.19	4.07
RE & RB	RB	1.20	6.22	8.69	12.42	18.42	27.66	41.31	60.57	63.42	63.26	62.34	58.47	49.54	34.35
Panel C: Delayed Policy															
i. with RE	RE	1.80	4.06	4.66	5.32	6.22	7.28	8.37	9.30	9.68	8.90	8.16	7.18	5.72	3.76
ii. with RB	RB	1.20	6.64	9.27	13.20	19.51	29.17	43.39	63.32	64.73	64.52	63.53	59.53	50.37	34.86
iii. with	RE	1.80	4.89	5.68	6.47	7.48	8.59	9.59	10.12	9.68	9.23	8.68	7.73	6.19	4.07
RE & RB	RB	1.20	6.22	8.70	12.42	18.43	27.65	41.30	60.55	63.39	63.22	62.30	58.43	49.51	34.33
Panel D: 2°C Policy															
i. with RE	RE	1.80	4.07	4.65	5.28	6.14	7.13	8.17	9.06	9.45	8.75	8.11	7.18	5.74	3.78
ii. with RB	RB	1.20	6.82	9.49	13.44	19.77	29.45	43.72	63.95	63.30	64.25	63.75	59.99	50.87	35.23
iii. with	RE	1.80	4.90	5.66	6.41	7.36	8.39	9.35	9.90	9.44	9.17	8.68	7.77	6.22	4.10
RE & RB	RB	1.20	6.45	8.98	12.76	18.84	28.15	41.94	61.59	60.97	63.01	62.55	58.90	50.01	34.70

Figure 2.1 presents a declined trend of backstop energy costs in the capital goods sector and in the consumption goods sector in the model with RE and RB over the time 150 years. A tiny difference of RB across different policy scenarios does not make a significant difference in backstop energy costs with an accuracy of 4 decimal points. Compared to the initial period, the backstop energy costs are reduced by 25.9% by 2055, 43.6% by 2105, and 53.6% by

2145. The IEA Technology Roadmap Wind Energy shows that the goal of cost reduction for wind energy is 25% in the land-based system and 45% in the offshore-based system by 2050. The IEA Technology Roadmap Solar Photovoltaic Energy suggests that the electricity costs from photovoltaic (PV) will be reduced by 65% by 2050. One reason why the decline in backstop energy costs is slightly slower than the above documents is that the energy costs are analyzed in the framework of a hybrid model with endogenous R&D in backstop energy rather than a pure bottom-up model. The declined trend of backstop price in this model is consistent with Popp (2006).

Figure 2.1 Declined Trends of Backstop Technology Costs in Two Sectors

The key rule of energy substitution follows the Ricardian comparative advantage theory. Each sector chooses the energy that has the comparative advantage, i.e., the fuel with the lowest energy costs (including extraction costs plus conversion costs). This model assumes a linear resource substitution. The sequence of resource use in the capital goods sector is oil products, coal products, and backstop energy, while the sequence of resource use in the consumption goods sector is natural gas, oil products, coal products, and backstop energy in all scenarios. The results are in line with (Chang, 1999). Table 2.2 shows the switching points of energy substitution in the capital goods sector and the consumption goods sector.

The switching points are the same across different scenarios within a case. In case i) and case ii), the backstop energy replaces fossil fuels by 2105 in the capital goods sector and by 2095 in the consumption goods sector. In the cases with RB (case iii and iv), the backstop energy is used ten years earlier than the cases without RB (case i and ii). Table 2.2 suggests that the R&D investments in backstop technology speed up the substitution between fossil fuels and backstop technology. Unlike the R&D investments in backstop technology, the R&D investments in energy efficiency do not make any contribution to the energy switching. The only role of the R&D investments in energy efficiency is reducing abatement costs.

Table 2.2 Switching Points of Energy Substitution

	Switching Points in Capital Goods Sector		Switching Points in Consumption Goods Sector		
	1 (Oil to Coal)	2 (Coal to Backstop)	1 (Gas to Oil)	2 (Oil to Coal)	3 (Coal to Backstop)
i. No RE & RB	2025	2105	2025	2035	2095
ii. with RE	2025	2105	2025	2035	2095
iii. with RB	2025	2095	2025	2035	2085
iv. with RE & RB	2025	2095	2025	2035	2085

Figure 2.2 shows an increase in atmosphere temperature compared to the pre-industry level across four scenarios. Each scenario presents temperature changes in four cases with or without RE and RB. Figure 2.2 shows that the highest temperature is achieved in 2115 in all the policy scenarios. After 2115 the atmospheric temperature declines even without any control policy. It happens as backstop energy substitutes fossil fuels that are dirty resources. Another interesting point is that the atmospheric temperature does not decrease right after backstop technology replaces fossil fuels. It takes time to achieve a desired reduction of temperature even though the energy used in production has already changed to a clean energy.

First, the temperature changes are analyzed across four policy scenarios. Figure 2.2 shows that the highest temperature reaches 2.77°C - 2.79°C above the pre-history level in the BAU

scenario. The atmospheric temperature in the optimal policy scenario is lower than that in the BAU scenario in every period. The highest temperature is around 2.54°C above the pre-history level in the optimal policy scenario, which is 0.24°C lower than the BAU scenario. For the delayed policy, the highest temperature is around 2.56°C above the pre-history level, which is lower than the BAU scenario but higher than the optimal policy scenario. Postponing the control policy by 10 years leads to an increase of 0.025°C compared to the policy implemented immediately. For the scenario of 2°C policy, the increase in atmospheric temperature is restricted within 2°C. After the highest point at 2115, the temperature keeps going down due to the substitution between backstop energy and fossil fuels, which leads to great economic gains after 2115.

Second, the impacts of RE and RB on temperature are presented within each scenario in Figure 2.2. Four cases with or without R&D investments generate similar tracks of atmospheric temperature. It means that environmental policy is a key for climate mitigation and that R&D investments lead to a small change in atmospheric temperature. Induced technological change have a more significant impact on welfare gains other than climate change, which is discussed continuously in Section 2.5.2. The findings are consistent with previous literature (Popp, 2004; Popp, 2006). Although the R&D is not significant to climate, the remaining paragraph still provides a difference in the impacts of RE and RB on atmospheric temperature.

Case i) and ii) have almost the same temperature paths. Similarly, case iii) and iv) have the same temperature paths. It means that RE rarely affects energy substitution as well as atmospheric temperature. Compared to case i) and ii), the temperature is higher in the case iii) and iv). The reason is that RB speeds up the substitution between fossil fuels and backstop energy. Fossil fuels are consumed slightly more in each period before the switching point from fossil fuels to backstop energy.

Figure 2.2 The Increase of Atmosphere Temperature (C) Compared to the Pre-history Level

2.5.2 Economic Gains and Abatement Costs

Three economic indicators quantify the economic gains induced by the abatement policy including the utility gains, the net present value (NPV) gains of consumption, and the NPV gains of output. The first two indicators measure the improvement of economic welfare resulting from control policies compared to the BAU scenario. The last one presents the increase in economic growth caused by the abatement policy. The control rates and the abatement costs in different policy scenarios are discussed together following the economic gains.

Table 2.3 summarizes the utility gains and the NPV gains of consumption and output across three policy scenarios compared to the BAU scenario. The utility gains are the percentage changes between the abatement policy scenario and the BAU scenario. The NPV gains of consumption (or output) are the NPV of consumption (or output) in the control policy scenario minus the NPV of consumption (or output) in the BAU scenario. The utility is

quantified by the percentage improvement, while the other two indicators are in the unit of constant 2005 trillion USD. The entire horizon is divided into three sub-periods: 2005-2045, 2055-2095, and 2105-2145, to show the impact of control policies in detail over 150 years.

**Table 2.3 Utility Gains (%), Net Present Value Gains of Consumption and Output (2005 Trillion USD)
Compared to the BAU Scenario**

	Utility Gains (%)	Net Present Value of Consumption Gains (2005 Trillion USD)				Net Present Value of Output Gains (2005 Trillion USD)			
	Period	Period 1	Period 2	Period 3	Period	Period 1	Period 2	Period 3	Period
	1-3 2005- 2145	2005- 2045	2055- 2095	2105- 2145	1-3 2005- 2145	2005- 2045	2055- 2095	2105- 2145	1-3 2005- 2145
Panel A: Optimal Policy									
i. No RE & RB	0.41%	-0.0080	0.2890	0.9886	1.2697	0.0136	0.4672	1.1431	1.6239
ii. with RE	0.39%	-0.0083	0.2878	0.9863	1.2657	0.0129	0.4569	1.1406	1.6104
iii. with RB	0.41%	-0.0232	0.3647	1.3376	1.6791	0.0088	0.4912	1.5579	2.0579
iv. with RE & RB	0.38%	-0.0371	0.4278	1.3559	1.7467	-0.0437	0.3975	1.5833	1.9371
Panel B: Delayed Policy									
i. No RE & RB	0.32%	0.0005	0.1795	0.8608	1.0408	0.0346	0.3220	0.9924	1.3491
ii. with RE	0.31%	-0.0003	0.1814	0.8619	1.0430	0.0330	0.3163	0.9939	1.3432
iii. with RB	0.33%	-0.0147	0.2504	1.1901	1.4258	0.0296	0.3437	1.3843	1.7575
iv. with RE & RB	0.31%	-0.0286	0.3154	1.2136	1.5004	-0.0220	0.2595	1.4156	1.6530
Panel C: 2°C Policy									
i. No RE & RB	-2.34%	-0.7627	-1.9770	2.7604	0.0207	-0.7642	-2.7745	3.1828	-0.3558
ii. with RE	0.39%	-0.7478	-2.0372	2.6961	-0.0889	-0.7314	-2.7395	3.0999	-0.3710
iii. with RB	-1.92%	-0.8100	-1.4379	3.5453	1.2974	-0.7581	-1.9827	4.1185	1.3777
iv. with RE & RB	-1.86%	-0.8096	-1.4520	3.5917	1.3301	-0.7859	-2.1509	4.1802	1.2434

The comparison across different policy scenarios (panel A-C) shows the improvement of utility is approximately 0.40% in the optimal policy scenario, 0.32% in the delayed policy scenario, and -1.43% (on average) in the 2°C policy scenario. It indicates that the delayed policy leads to less economic welfare gains compared to the optimal policy and that the strict policy reduces the economic welfare in a large amount. The NPV gains of consumption and output have similar trends. In period 1, the NPV gains of consumption in the optimal policy scenario are less than those in the BAU scenario, while the case goes to the opposite way in period 2 and period 3. It means that although the optimal policy restrains the welfare gains

in the short run, it benefits the economic welfare more in the long-run. These results are in line with Popp (2006). The NPV gains of output are positive but quite small in period 1 in most cases of the optimal scenario and the delayed scenario, while the NPV gains of output increase over time. The NPV gains of output in the delayed policy scenario are higher than those in the optimal policy scenario in period 1 while the performance in the delayed policy scenario gets worse than that in the optimal policy scenario in last two periods. It means that postponing ten years to implement the control policy benefits the output and consumption in the short run but sacrifices the economic welfare in the long run. With the 2°C policy, the NPV gains of output and consumptions are less than those in the BAU scenario in period 1 and period 2, but the NPV gains of output and consumptions are larger than those in the BAU scenario in period 3. It indicates that the restrictive policy sacrifices the economic welfare more in the short-term but brings more benefit in the long-term. The comparison across three control policies shows that the optimal policy leads to larger NPV gains of output and consumptions than the other two control policies over the time span from 2005 to 2145.

Table 2.3 shows the impact of energy R&D investments on the NPV gains of consumption and output. The results in three periods indicate that energy R&D investments significantly affect the NPV gains of consumption and output in the third period from 2105 to 2155 than that in the first period and the second period. It provides an important implication that the knowledge is cumulative and that small changes in the R&D give an important long-run effect. This conclusion is in line with existing literature (Popp, 2004; Popp, 2006).

The comparison within each panel (case i-iv) in Table 2.3 shows the impact of RE on economic gains by comparing case i and case ii OR by comparing case iii and case iv. RE reduces the utility gains and the NPV gains of output, which seems to be against the economic intuition at the first glance since RE improves the energy efficiency in the

production. However, this point makes sense, which is further illustrated in the analysis of abatement costs in details. The impact of RE on the NPV gains of consumption is ambiguous. The contribution of RB is shown by comparing case i and case iii OR by comparing case ii and case iv. RB greatly improves the utility gains and the NPV gains of consumption and output through the indirect channel of the change of energy substitution illustrated as follows. RB significantly lowers the costs of backstop energy. As the backstop energy has infinite stock, the quantity of energy use goes up due to the reduction of backstop costs, which leads to an increase in output and consumption.

Table 2.4 presents the output over 150 years in detail. The output is in the unit of constant 2005 trillion USD. The output declines in early periods in the optimal policy scenario and the 2°C policy scenario compared to the BAU scenario due to the abatement costs. With the efforts of emissions abatement, there is an increase in the output in the optimal policy scenario and the 2°C policy scenario compared to the BAU scenario in late periods. For the optimal scenario, the ‘catching-up’ year is 2035 in case i, ii, and iii, and 2055 in case iv. For the 2°C policy scenario, the ‘catching-up’ year is 2105 in case i and ii, and 2095 in case iii and iv. The gap of ‘catching-up’ points between the optimal scenario and the 2°C scenario shows that the output gets more harmed in a more restrictive policy scenario in the early periods. For the delayed policy scenario, although the output is higher than the BAU scenario in all periods, the accumulated NPV of output is still less than that in the optimal policy scenario as it is shown in Table 2.3.

Table 2.4 Output (2005 Trillion USD)

Output (2005 Trillion USD)	2005	2015	2025	2035	2045	2055	2065	2075	2085	2095	2105	2145
Panel A: BAU												

i. No RE & RB	47.09	61.74	73.57	87.05	104.30	124.54	147.49	173.18	202.37	219.58	247.59	381.65
ii. with RE	47.09	61.79	73.66	87.27	104.69	125.16	148.39	174.37	203.83	222.62	250.86	387.58
iii. with RB	47.09	61.74	73.59	87.37	105.05	125.93	149.89	177.28	198.84	227.58	264.76	434.17
iv. with RE & RB	47.09	61.81	73.70	87.68	105.61	126.82	151.21	179.11	201.17	230.64	268.49	440.92
Panel B: Optimal Policy												
i. No RE & RB	47.09	61.74	73.55	87.05	104.35	124.67	147.76	173.65	203.21	219.11	248.21	383.63
ii. with RE	47.09	61.79	73.64	87.28	104.74	125.28	148.64	174.83	204.65	222.17	251.48	389.56
iii. with RB	47.09	61.74	73.57	87.37	105.09	126.06	150.17	177.83	198.67	228.24	265.93	436.59
iv. with RE & RB	47.09	61.81	73.68	87.65	105.59	126.82	151.26	179.23	201.59	231.42	269.74	443.32
Panel C: Delayed Policy												
i. No RE & RB	47.09	61.74	73.58	87.06	104.33	124.63	147.69	173.55	203.07	219.03	248.08	383.42
ii. with RE	47.09	61.79	73.66	87.29	104.73	125.25	148.58	174.74	204.52	222.09	251.35	389.35
iii. with RB	47.09	61.74	73.60	87.38	105.08	126.02	150.10	177.73	198.58	228.10	265.76	436.36
iv. with RE & RB	47.09	61.81	73.71	87.66	105.58	126.79	151.20	179.15	201.48	231.29	269.58	443.09
Panel D: 2°C Policy												
i. No RE & RB	47.09	61.75	73.42	86.64	103.58	123.42	145.92	171.21	200.46	218.33	249.02	387.42
ii. with RE	47.09	61.80	73.51	86.89	104.01	124.09	146.90	172.56	202.24	220.71	252.05	393.39
iii. with RB	47.09	61.75	73.45	86.96	104.32	124.80	148.40	175.91	196.77	228.63	267.50	440.86
iv. with RE & RB	47.09	61.81	73.57	87.26	104.84	125.60	149.55	177.44	198.90	232.11	271.38	447.58

The results show the impact of RE on the output by comparing case i and case ii OR by comparing case iii and case iv within each panel. The output levels are higher in the cases with RE than the cases without RE. The difference of output in the cases with and without endogenous RE is more significant in late periods than that in early periods due to an accumulation effect of knowledge stocks. This explains why the NPV gains of output with RE are lower than those without RE in Table 2.3 since the gains in later periods have a less NPV considering the rate of social preference. The results provide the contribution of RB to the output by comparing case i and case iii OR by comparing the case ii and case iv. The output is higher when RB is taken into account endogenously. Similar to the analysis of RE, the difference with and without endogenous RB is more obvious in late periods due to the accumulation of knowledge stocks in backstop technology than that in early periods. The results also show the difference in the impacts of R&D investments in energy efficiency and backstop technology. RB contributes more to the increase in output than RE.

Table 2.5 shows the control rates across different policies. Table 2.6 presents the abatement costs in different policy scenarios. The control rate is in the unit of percentage, while the abatement costs are in the unit of constant 2005 USD. Across different panels, the control rates in the optimal policy scenario are slightly lower than those in the delayed policy scenario. It indicates that the control rate is more restrictive if the policy is postponed ten years to implement. The abatement costs account for approximately 0.02% in the share of total NPV of output in the optimal policy scenario, while they are a little higher in the delayed policy scenario than those in the optimal policy scenario, which is in line with the trend of control rate. For the 2°C policy, the control rate is 2 to 3 times of that in the optimal policy. The abatement costs account for 0.49% in the share of total NPV of output in the 2°C policy scenario, which are much more than the optimal policy scenario.

Within each panel, the control rates and abatement costs in case ii and case iv are lower than those in case i and case iii. The reason is that the improvement in energy efficiency reduces the energy consumption in each period due to the substitution effect between the resource and the knowledge stock of energy. The control rates and abatement costs in case iii and iv are higher than those in case i and ii within a panel as RB hastens the rate at which fossil fuels are obsolete and encourages the consumption of fossil fuels in early periods. The pattern of abatement costs within a panel is consistent with the pattern of control rates.

Table 2.5 Emissions Control Rates (%)

Control Rates (%)	2005	2015	2025	2035	2045	2055	2065	2075	2085	2095	2105-2145
Panel A: Optimal Policy											
i. No RE & RB	-	-	19.8%	21.3%	20.9%	20.2%	18.9%	17.0%	14.5%	1.5%	0.0%
ii. with RE	-	-	19.5%	21.2%	20.8%	20.0%	18.7%	16.8%	14.4%	2.8%	0.0%
iii. with RB	-	-	19.7%	22.0%	21.8%	21.2%	19.9%	17.9%	5.0%	0.0%	0.0%
iv. with RE & RB	-	-	19.2%	21.9%	21.6%	21.0%	19.7%	17.7%	6.2%	0.0%	0.0%
Panel B: Delayed Policy											
i. No RE & RB	-	-	-	21.4%	21.0%	20.2%	18.9%	17.0%	14.6%	1.6%	0.0%
ii. with RE	-	-	-	21.2%	20.9%	20.1%	18.8%	16.9%	14.4%	2.9%	0.0%

iii. with RB	-	-	-	22.1%	21.9%	21.3%	20.0%	18.0%	5.1%	0.0%	0.0%
iv. with RE & RB	-	-	-	21.9%	21.7%	21.0%	19.8%	17.8%	6.3%	0.0%	0.0%
Panel C: 2 °C Policy											
i. No RE & RB	-	-	40.1%	47.7%	52.9%	58.2%	62.8%	65.3%	63.3%	0.1%	0.0%
ii. with RE	-	-	39.5%	47.7%	52.9%	58.2%	62.9%	65.4%	63.4%	0.1%	0.0%
iii. with RB	-	-	39.3%	48.8%	54.7%	60.7%	65.3%	65.9%	0.1%	1.4%	0.0%
iv. with RE & RB	-	-	38.5%	48.5%	54.3%	60.3%	65.0%	65.6%	0.1%	3.5%	0.0%

Table 2.6 Abatement Costs (2005 Billion USD)

Abasement Cost (2005 Billion USD)	2005	2015	2025	2035	2045	2055	2065	2075	2085	2095	2105- 2145
Panel A: Optimal Policy											
i. No RE & RB	-	-	29.55	47.53	56.66	65.04	67.76	61.22	48.87	0.11	0.00
ii. with RE	-	-	28.24	46.88	55.83	64.01	66.58	60.03	47.82	0.64	0.00
iii. with RB	-	-	28.97	52.66	64.55	76.00	80.59	73.58	2.66	0.00	0.00
iv. with RE & RB	-	-	27.33	51.59	63.17	74.31	78.75	71.83	4.88	0.00	0.00
Panel B: Delayed Policy											
i. No RE & RB	-	-	-	47.87	57.06	65.46	68.16	61.55	49.12	0.14	0.00
ii. with RE	-	-	-	47.20	56.22	64.41	66.95	60.34	48.05	0.69	0.00
iii. with RB	-	-	-	53.02	64.99	76.48	81.05	73.97	2.77	0.00	0.00
iv. with RE & RB	-	-	-	51.95	63.64	74.83	79.26	72.27	4.91	0.00	0.00
Panel C: 2 °C Policy											
i. No RE & RB	-	-	213.49	453.01	755.70	1259.40	1958.24	2652.74	3010.90	0.00	0.00
ii. with RE	-	-	205.17	452.91	758.18	1268.20	1978.53	2686.00	3048.16	0.00	0.00
iii. with RB	-	-	201.81	488.35	842.64	1443.93	2250.80	2831.42	0.00	0.09	0.00
iv. with RE & RB	-	-	190.64	480.74	830.70	1426.17	2228.77	2815.43	0.00	1.22	0.00

2.6 Conclusion

This study investigates the impacts of emissions abatement policies and energy R&D investments on resource use, climate change, economic gains, and abatement costs over the time span from 2005 to 2145. This study analyzes three emission-control policies including optimal policy, delayed policy, and 2 °C policy proposed by the Paris Agreement. This study explicitly identifies two types of R&D investments: a) the R&D investments in energy efficiency and b) the R&D investments in backstop technology. This study develops a hybrid model with endogenous energy R&D investments linking the bottom-up model to the top-down model. This study expects to contribute to the literature by four key findings. First, the

study explores the roles of energy R&D investments with respect to the economic welfare, energy substitution, and climate change. Second, the study presents the resource use sequences in the capital goods sector and the consumption goods sector, which shows how soon the backstop technology replaces the fossil fuels. Third, the study presents the trends of atmospheric temperature in four policy scenarios. Last, it analyzes the impacts of emissions control policies on the economic gains and the abatement costs. The results present the paths of the key indicators including utility gains, the NPV gains of consumption and output, output trends, control rates, and abatement costs.

The simulations of the hybrid model present four key findings that are different from existing studies, which are demonstrated in details as follows. First, this study finds that the roles of two types of energy R&D investments are different in the impacts on energy substitution and economic welfare. The R&D investments in energy efficiency improve the energy services used in production given the amount of raw energy. The key role of R&D investments in energy efficiency is to reduce the abatement costs induced by the abatement policy. Different from the R&D investments in energy efficiency, the R&D investments in backstop energy lower the costs of backstop technology and further boost the substitution between fossil fuels and backstop energy. The replacement of backstop for fossil fuels is completed earlier of ten years in the model with RB than the model without RB. More fossil fuels are used in earlier years in the case with endogenous RB than the case without endogenous RB, which leads to a higher temperature in the corresponding periods in the case with endogenous RB.

Second, this study investigates the resource substitution using models with and without the R&D investments. The results conform to the Ricardian comparative advantage theory, i.e., each sector chooses the fuel with the lowest cost in the current period. Following this rule, the sequences of resource use are a) oil products, followed by coal products, followed by

backstop energy in the capital goods sector, and b) gas, followed by oil products, followed by coal products and followed by backstop energy in the consumption goods sector. The backstop energy replaces fossil fuels in capital goods sector in 2105 (without RB case) or 2095 (with RB case), and substitute fossil fuels in consumption goods sector in 2095 (without RB case) or 2085 (with RB case).

Third, this study further explores the impact of energy-related carbon emissions on the change of atmospheric temperature. The atmospheric temperature climbs up and then goes down after the backstop technology replaces the fossil fuels. In the BAU scenario, the highest atmospheric temperature is reached at 2.78°C in 2115. However, the highest atmospheric temperature is constrained at 2.53°C in 2115 in the optimal policy scenario, and at 2.56°C in 2115 in the delayed policy scenario. The optimal policy lowers the highest atmospheric temperature by 0.25°C compared to the BAU scenario. In 2°C policy scenario, the highest atmospheric temperature is also achieved in 2115.

Fourth, this study analyzes the economic gains and abatement costs across different policies using the models with and without R&D investments. The utility is improved of 0.38% - 0.41% by the optimal policy, of 0.31% - 0.33% by the delayed policy, of -2.34% - 0.39% by the 2°C policy, over the time 150 years.⁵ The entire time span is divided into three equivalent parts for detailed analysis. The improvement of the NPVs of output and consumption are not significant in the first two sub-periods (2005-2095), but the NPVs of output and consumption are greatly enhanced by the emissions abatement policy in the last sub-period (2105-2145). The results also indicate that a restrictive policy hurts the economic welfare more in the short run, as well as, benefits the economic welfare more in the long run compared to a less restrictive policy. The abatement costs account for approximately 0.02%

⁵ The range covers the results in four cases with and without R&D.

in the share of total NPV of output in the optimal policy scenario and in the delayed policy scenario. The abatement costs account for 0.49% in the share of total NPV of output in the 2 °C scenario, which are much more than the optimal policy scenario.

2.7 Appendix: A Full List of Equations

2.7.1 Exogenous Variables and Parameters

t	time
i	1=capital goods sector, 2=consumption goods sector
L_t	total population at time t , also equal to labor inputs
$L_{1,t}$	population in capital goods sector at time t
$L_{2,t}$	population in consumption goods sector at time t
L_0	the initial population level
$g_{L,t}$	the growth rate of population
$g_{L,0}$	the initial value of the growth rate of population
d_L	the rate of decline of the growth rate of population
r	pure rate of social time preference (per unit time)
R_t	social time preference discount factor (per period)
α	the elasticity of marginal utility of consumption (pure number)
A_t	total factor productivity
A_0	the initial value of total factor productivity
$g_{A,t}$	the growth rate of total factor productivity
$g_{A,0}$	the initial value of the growth rate of total factor productivity
d_A	the rate of decline of the growth rate of total factor productivity
β_i, γ_i	elasticity parameter in production function in sector i
a_1, a_2	parameters of damage function

θ_1, θ_2	parameters of the abatement cost function
δ_K	the rate of depreciation of physical capital (per period)
δ_H	the rate of depreciation of knowledge stock (per period)
ρ	substitution parameter for raw energy and knowledge
$S_{J,0}$	proved reserve of fossil fuel J in 2005 (J=P, W, G, namely, oil, coal, and gas)
$z_{i,j,t}$	energy cost of fossil fuel j used in sector i (J=P, W, G, namely, oil, coal, and gas)
$z_{i,B,0}$	the initial cost of backstop energy in sector i
$\varphi_{E,1}, \varphi_{E,2}, \varphi_{E,3}, \varphi_{B,1}, \varphi_{B,2}, \varphi_{B,3}$	parameters of new knowledge stock
LU_t	land-use carbon emissions
LU_0	initial land-use carbon emissions
d_{LU}	the rate of decline of land-use carbon emissions
η_P, η_W, η_G	emission-factors of oil products, coal products, and natural gas
$\phi_{11}, \phi_{12}, \phi_{21}, \phi_{22}, \phi_{23}, \phi_{32}, \phi_{33}$	parameters of the carbon transition matrix
$F_{EX,t}$	the increase in radioactive forcing over preindustrial levels due to exogenous anthropogenic causes
$\sigma_1, \sigma_2, \sigma_3, \sigma_4$	temperature dynamics parameters

2.7.2 Endogenous Variables

U_t	utility in period t
c_t	per capita consumption of goods and services (constant 2005 USD per person)
Q_t	total net output (trillions of constant 2005 USD)
$Q_{i,t}$	net output in capital sector i (trillions of constant 2005 USD)

Ω_t	damage function (climate damages as a fraction of world output)
Λ_t	abatement cost function (abatement costs as a fraction of world output)
μ_t	emissions-control rate (fraction of uncontrolled emissions)
K_t	total physical capital stock (trillions of constant 2005 USD)
$K_{i,t}$	physical capital stock in sector i (trillions of constant 2005 USD)
I_t	investments in physical capital (trillions of constant 2005 USD)
$ES_{i,t}$	energy service used in sector i
$ER_{i,t}$	raw energy used in sector i
$P_{i,t}$	oil products used in sector i
$W_{i,t}$	coal products used in sector i
$G_{i,t}$	natural gas used in sector i
$B_{i,t}$	backstop energy used in sector i
$CE_{i,t}$	energy cost in sector i
$z_{i,B,t}$	energy cost of backstop energy in sector i
b	the scale factor of the energy cost of backstop energy
$R_{E,t}$	R&D investments in energy efficiency
$R_{B,t}$	R&D investments in backstop technology
$H_{E,t}$	knowledge stock on energy efficiency
$H_{B,t}$	knowledge stock on backstop technology
EM_t	total carbon emissions
E_t	energy-related carbon emissions

$M_{A,t}$	atmospheric CO2 concentration
$M_{U,t}$	upper oceans/biosphere CO2 concentration
$M_{L,t}$	lower oceans CO2 concentration
F_t	radioactive forcing, increase over the preindustrial level
T_t	atmospheric temperature, increase over 1900 level
TL_t	lower ocean temperature, increase over 1900 level

2.7.3 Equation List

$$(A.1) \quad \max V = \sum_{t=1}^T U_t(c_t, L_t) R_t$$

$$(A.2) \quad U_t(c_t, L_t) = L_t \left[c_t^{1-\alpha} / (1-\alpha) \right]$$

$$(A.3) \quad Q_t = \sum_{i=1,2} Q_{i,t}$$

$$(A.4) \quad Q_{i,t} = \Omega_t (1 - \Lambda_t) A_t K_{i,t}^{\beta_i} E S_{i,t}^{\gamma_i} L_{i,t}^{1-\beta_i-\gamma_i} - C E_{i,t}, i=1,2$$

$$(A.5) \quad \Omega_t = 1 / (1 + a_1 T_t + a_2 T_t^2)$$

$$(A.6) \quad \Lambda_t = \theta_t \mu_t^{\theta_2}$$

$$(A.7) \quad L_t = L_0 \exp(g_{L,t})$$

$$(A.8) \quad g_{L,t} = (g_{L,0} / d_L) * (1 - \exp(-d_L * t))$$

$$(A.9) \quad A_t = A_0 \exp(g_{A,t})$$

$$(A.10) \quad g_{A,t} = (g_{A,0} / d_A) * (1 - \exp(-d_A * t))$$

$$(A.11) \quad K_t = I_t + (1 - \delta_K) K_{t-1}$$

$$(A.12) \quad ES_{i,t} = (ER_{i,t}^\rho + H_{E,t}^\rho)^{1/\rho}$$

$$(A.13) \quad ER_{i,t} = P_{i,t} + W_{i,t} + G_{i,t} + B_{i,t}$$

$$(A.14) \quad S_{J,0} \geq \sum_{t=1}^T (J_{1,t} + J_{2,t}), J = P, W, G$$

$$(A.15) \quad CE_{i,t} = z_{i,P,t} P_{i,t} + z_{i,W,t} W_{i,t} + z_{i,G,t} G_{i,t} + z_{i,B,t} B_{i,t}$$

$$(A.16) \quad z_{i,B,t} = \frac{z_{i,B,0}}{(H_{B,t})^b}$$

$$(A.17) \quad H_{m,t} = h(R_{m,t}) + (1 - \delta_H) H_{m,t-1}, m = E, B$$

$$(A.18) \quad h(R_{m,t}) = \varphi_{m,1} R_{m,t}^{\varphi_{m,2}} H_{m,t}^{\varphi_{m,3}}, m = E, B$$

$$(A.19) \quad Q_{1,t} = I_t + R_{E,t} + R_{B,t}$$

$$(A.20) \quad Q_{2,t} = C_t$$

$$(A.21) \quad EM_t = E_t + LU_0 (1 - \delta_{LU})^t$$

$$(A.22) \quad E_t = (1 - \mu_t)(\eta_P P_t + \eta_W W_t + \eta_G G_t)$$

$$(A.23) \quad M_{A,t} = 10 * EM_t + \phi_{33} M_{A,t-1} + \phi_{23} M_{U,t-1}$$

$$(A.24) \quad M_{U,t} = \phi_{12} M_{A,t-1} + \phi_{22} M_{U,t-1} + \phi_{33} M_{L,t-1}$$

$$(A.25) \quad M_{L,t} = \phi_{11} M_{L,t-1} + \phi_{21} M_{U,t-1}$$

$$(A.26) \quad F_t = 4.1 * [\log_2 (M_{A,t} / M_{A,1750})] + F_{EX,t}$$

$$(A.27) \quad T_t = T_{t-1} + \sigma_1 [F_t - \sigma_2 T_{t-1} - \sigma_3 (T_{t-1} - TL_{t-1})]$$

$$(A.28) \quad TL_t = TL_{t-1} + \sigma_4 (T_{t-1} - TL_{t-1})$$

3 Essay 2: Energy Consumption and Carbon Emissions in the APEC-17 Countries: Trends and Drivers

3.1 Introduction

Energy consumption and corresponding carbon emissions are posing a daunting question to policymakers, academics and the public alike in terms of whether they move in tandem, what drives the co-movement and what factors are behind the trend. Currently, the Asia-Pacific Economic Cooperation (APEC) is the largest regional organization by energy consumption. The overall energy consumption in the APEC region was 2,848.10 Mtoe in 1990 and 4,380.58 Mtoe in 2010, which increases by 53.81% over twenty years.⁶ Energy-related carbon emissions are key components of total emissions. Controlling energy-related carbon emissions helps mitigate global warming and promotes sustainable development. Exploring the trends and drivers of energy consumption and carbon emissions gives a good understanding of historical tendency in the APEC region and also provides policy implications for the future energy consumption.

The APEC region covers eleven developed countries (including special administrative regions) and ten developing countries.⁷ The diversity in economic development and energy consumption among member countries arouses the interests to look into the features of the energy consumption and carbon emissions in this region. Table 3.1 summarizes the energy consumption, carbon emissions, and value-added in top four developed countries and

⁶ The data is collected from the IEA database. The data excludes Russia because the data is not available during the breakup of the Soviet Union.

⁷ Based on the income per capita provided by the World Bank, the developed countries (or special administrative regions) include Australia, Brunei, Canada, Chile, Hong Kong, Japan, Korea, New Zealand, Singapore, Taiwan, and United States. The developing countries include China, Indonesia, Malaysia, Mexico, Papua New Guinea, Peru, Philippines, Russia, Thailand, and Vietnam. Russia is classified into “high-income economies” by the World Bank from 2012.

developing countries of the APEC region based on the quantity of energy consumption.⁸ Table 3.1 shows that the absolute values of energy consumption and CO₂ in developing countries are much smaller than those in developed countries while the growth rate of energy consumption and energy-related carbon emissions is much higher in developing countries than that in developed countries. The value-added data also show that the developing economies experience faster economic growth than the developed economies in the APEC region from 1990 to 2010. The comparison between the growth rates of energy consumption and value-added indicates that the developed countries experience a reduction of energy intensity while the developing countries, except China, do not experience such a decline in energy intensity. The trends of carbon intensity are similar to the trends of energy intensity in above countries.

The underlying implication of the trend of energy consumption and carbon emissions is that developed countries and developing countries of the APEC region have different patterns regarding energy consumption, energy intensity, carbon emissions, and carbon intensity. It motivates this study to explore the trends and drivers of energy consumption and carbon emissions in each country of the APEC region. Identifying the drivers not only gives explanations for the difference in energy use pattern and carbon emissions pattern between developed and developing countries but also sheds light on the heterogeneity in the essential challenges of energy conservation and carbon reduction between developed and developing countries. Understanding the trends and drivers of energy consumption and carbon emissions in the APEC developing countries further provides a reference to the policy makers in other developing countries beyond this region.

Table 3.1 Major Indicators in Top 4 Developed Countries and Developing Countries of the APEC

Region

⁸ This study excludes Russia because the data is not available during the breakup of the Soviet Union.

	Energy Consumption ⁹			Carbon Emissions ¹⁰			Value-added		
	Quantity (Mtoe) in 1990	Quantity (Mtoe) in 2010	Average Annual Growth Rate	Quantity (MtCO ₂) in 1990	Quantity (MtCO ₂) in 2010	Average Annual Growth Rate	const. 2005 USD in 1990	const. 2005 USD in 2010	Average Annual Growth Rate
Panel A: Top 4 Developed Countries in the APEC Region									
USA	965	1,097	0.65%	3,393	3,882	0.67%	8,808	13,486	2.15%
JPN	225	232	0.16%	775	804	0.18%	3,832	4,571	0.89%
CAN	115	134	0.76%	316	367	0.76%	725	1,162	2.38%
ROK	45	99	4.02%	142	387	5.16%	350	1,000	5.39%
Panel B: Top 4 Developing Countries in the APEC Region									
PRC	402	1,342	6.22%	1,831	6,493	6.53%	546	3,828	10.22%
IDN	36	111	5.81%	124	393	5.93%	148	377	4.76%
MEX	59	88	1.95%	193	286	2.00%	543	916	2.64%
THA	21	48	4.33%	73	170	4.35%	94	225	4.48%

The existing literature investigates the drivers of energy consumption and carbon emissions from sectoral approach or national approach - focusing on developed countries (Hojjati and Wade, 2012; Cansino *et al.*, 2015) or analyzing developing countries (Das and Paul, 2013; Zhang *et al.*, 2016). The unavailability of energy data in many developing countries is the main cause of relatively fewer studies on developing economies. Among the studies for developing countries, most frequently studied economies are China, India, and Thailand. Other emerging developing countries that also experience rapid economic and energy growth over the past twenty years, such as Vietnam and Indonesia, are rarely studied. Upon identifying the limitation of the existing studies, this essay mainly makes two contributions to the literature. First, this study uses the energy dataset with high quality in the APEC region over twenty years from 1990 to 2010. The energy data are mainly from the IEA database and also referring to the local data and the datasets released by the APEC Energy Working Group (EWG). Second, this study contributes to the literature by exploring the energy

⁹ Energy consumption refers to the energy used to increase value-added, which is collected from the IEA database.

¹⁰ Carbon emissions are calculated based on the energy consumption in the IEA database and the emission-factors in the IPCC 1996. Here, the carbon emissions are only caused by the energy consumption to increase value-added.

consumption and carbon emissions in a large group of developing countries. This study covers a long time span from 1990 to 2010 and emphasizes the difference in trends, drivers, and policy implications between developed countries and developing countries.

This study aims to address the following three research questions regarding the heterogeneity of energy use pattern and carbon emissions in developed and developing countries in the APEC region. First, this study identifies the key drivers of energy consumption in developed and developing countries of the APEC region and analyzes the difference in energy use pattern between developed and developing countries. Second, this study decomposes the energy-related carbon emissions and measures the impact of energy structure change on the carbon emissions. The study also discusses the features of carbon emissions in both developed countries and developing countries. Third, this study examines the change of energy consumption and carbon emissions given a macroeconomic shock in 1998 and 2008. The results show that the negative macroeconomic shocks affect the energy consumption and carbon emissions mainly through the channel of activity effect. They have little impacts on other factors, such as intensity effect.

The remaining essay is organized as follows. Section 3.2 presents a summary of the existing literature for methodology and application. Section 3.3 introduces the temporal IDA model used to decompose the energy consumption and carbon emissions in this study. Section 3.4 presents the data used in this study including value-added data, energy mix data, and emission factors. Section 3.5 discusses the decomposition results of energy consumption and carbon emissions in both developed and developing countries. Section 3.6 concludes the study.

3.2 Literature Review: Methodology and Application

This section reviews the recent literature of Index Decomposition Analysis (IDA) studies. Section 3.2.1 presents the history of the IDA method and the criteria to choose a

decomposition scheme. Section 3.2.2 reviews the recently applied studies that use decomposition analysis to evaluate the energy consumption and carbon emissions in developed countries. Section 3.2.3 reviews the applied studies focusing on developing countries. As a few survey studies (Ang and Zhang, 2000; Xu and Ang, 2013) have covered many existing applied studies of energy consumption and carbon emissions, section 3.2.2 and 3.2.3 reviews only recent applied studies that are not covered by those survey studies.

3.2.1 A Methodology Review: Decomposition Scheme

Decomposition schemes broadly contain two families: the method associated with the Divisia index and the method associated with the Laspeyres index. Each index family has an additive version and a multiplicative version.

The Divisia index family employs the weights in the function form of the logarithmic mean of two variables. The IDA methods based on the Divisia index family include the arithmetic mean Divisia index method (AMDI) (Ang, 2004), the log mean Divisia index method I (LMDI I) (Boyd, 1987; Boyd *et al.*, 1988), and the log mean Divisia index method II (LMDI II) (Ang and Choi, 1997). The AMDI with an arithmetic mean weight function gives large residuals, while the LMDI I and II with a logarithmic mean weight function provide perfect decomposition results. The additive LMDI I retains the property of perfect decomposition at the sub-category level, while the additive LMDI II does not have this property. However, the sum of residuals of LMDI II is zero at the sub-category level. Both the AMDI and the LMDI II can transfer to the LMDI I by redistributing the residual terms proportionally based on the sub-category (Ang *et al.*, 2009).

The Laspeyres index family with the weights quantifying the percentage change of two variables includes the modified Fisher ideal index method (Ang *et al.*, 2002) and the Shapley / Sun method (Sun, 1998; Albrecht *et al.*, 2002). The former method is in a multiplicative form, while the latter method is in an additive form. The modified Fisher ideal index method

gives perfect decomposition results overcoming the disadvantage of the conventional Fisher ideal index method. The Sun method is consistent with the Shapley value method by defining a characteristic function and applying an allocation principle (Ang, 2004; Ang *et al.*, 2009). Ang (2004) proposes four rules to assess if a decomposition scheme is ideal in applied studies. The criteria are (a) theoretical foundation, (b) adaptability, (c) ease of use, and (d) ease of result interpretation. The theoretical index number theory evaluates a method by the following tests: time-reversal test, factor-reversal test, proportional test, and aggregation test. The adaptability requires that a method is suitable in both time-series and the cross-country analysis. The ease of use and results interpretation concerns a practical application and a straightforward explanation of the results.

This study uses the multiplicative LMDI I (M-LMDI I) method based on the Divisia index family as this method has several advantages as follows. First, it passes the time-reversal test meaning that the M-LMDI I method measures the relative change. No matter which year is the baseline, the relative change remains the same. Second, it passes the factor reversal test indicating that there is no residual term leading to a perfect decomposition and a transparent explanation. Third, the M-LMDI I method satisfies the consistent condition in the regional analysis ensuring that the results are the same whichever sub-level each country chooses. A chained M-LMDI I is used in this study for each single period. The chained method minimizes the time interval and approximates the index better than the non-chained method.

3.2.2 An Application Review: Developed Countries

Many studies investigate the drivers of energy consumption and energy intensity in developed countries. Many recent studies in developed countries focus on a specific sector, as high-resolution datasets in a specific sector become available in developed countries. For example, the studies in industry sector include Hasanbeigi *et al.* (2012), Choi and Oh (2014),

and Duran *et al.* (2015); the studies in residential sector include Hojjati and Wade (2012) and Rogan *et al.* (2012); the study in service sector includes Mairet and Decellas (2009). A few studies are from the approach of national energy consumption or energy intensity, such as Baležentis *et al.* (2011) and Shahiduzzaman and Alam (2013). These studies are in a time frame of 10 - 15 years since the high-resolution data in a specific sector are not available for a long period. The studies from a sectoral approach or a national approach conclude that the energy intensity is a key factor contributing to the reduction of energy consumption as the energy efficiency improves across different sectors in developed countries.

Several studies explore the driving forces of energy-related carbon emissions in developed countries. Some of them are from sectoral approach including manufacturing sector and transport sector (Hammond and Norman, 2012; O' Mahony *et al.*, 2012; Fujii and Managi, 2013; Sobrino and Monzon, 2014), while some of them are from a national approach (Cansino *et al.*, 2015; Shahiduzzaman *et al.*, 2015). The results indicate that the economic growth is a leading factor causing an increase in carbon emissions, while the reduction of energy intensity is the key driver that lowers energy-related carbon emissions in developed countries. Fuel mix effect also significantly reduces the carbon emissions in the European countries. The change of economic structure leads to a decline in carbon emissions in a moderate way.

3.2.3 An Application Review: Developing Countries

Many studies identify the impact of economic growth, economic structure, and sectoral energy intensity on energy consumption and energy intensity in developing countries. A lot of studies focus on China and India that are two large emerging countries. The existing studies examine the above effects from a national approach (Ma and Stern, 2008) and a sectoral approach. The study from sectoral approach includes the energy consumption in industry sector (Bhattacharyya and Ussanarassamee, 2005; Hasanbeigi *et al.*, 2013), in

transport sector (Mraihi *et al.*, 2013; Tiwari and Gulati, 2013), and in residential sector (Zhao *et al.*, 2012; Das and Paul, 2013). The results provide the evidence that economic growth greatly drives up energy consumption, while the decline in sectoral energy intensity slightly offsets the effect of economic growth in developing countries. Although the energy intensity declines significantly in China, it does not decrease apparently in other developing countries, such as Thailand. In contrast to developed countries, the change of economic structure in developing countries has a positive impact on the energy consumption. It indicates that the economy shifts to the energy-intensive sector, as well as, that the energy use pattern within a specific sector tends to become more energy-intensive. For example, an increasing shift towards private vehicle leads to an increase of energy consumption of transport sector in India (Tiwari and Gulati, 2013).

Recently, carbon emissions in developing countries draw much attention by scholars. The key drivers that determine the carbon emissions and air pollution are explored by some studies (Fujii *et al.*, 2013; Li *et al.*, 2013; Zhang *et al.*, 2013; Das and Paul, 2014; Lin and Lei, 2015; Zhang *et al.*, 2016). Some studies are from a national approach while some of them are from a sector approach, specifically in industry sector, transport sector, and residential sector. The effects of economic growth and sectoral energy intensity in developing countries are similar to those in developed countries, while the effect of economic structure makes a contribution to the increase in carbon emissions in developing countries, which is different from the case in developed countries. Also, the contribution of fuel mix effect to the carbon emissions is not clear in developing countries, which is quite different from developed countries.

Section 3.2.2 and 3.2.3 provide an overview of the literature related to index decomposition analysis of energy consumption and carbon emissions in developed and developing countries. These two clusters of paper show that although the key drivers of energy consumption and carbon emissions are economic growth and sectoral energy intensity in both developed and

developing countries, the magnitude of these two effects is very different between developed countries and developing countries. The booming economy makes more contribution to the increase in energy consumption and carbon emissions in developing countries than in developed countries due to the high economic growth rate, while the reduction of energy intensity is not so significant in most developing countries except China. Also, the impact of economic structure change on energy consumption and carbon emissions is also different between developed countries and developing countries. The economy shifts toward to less energy-intensive sectors in developed countries while developing countries do not show the same pattern.

Although the existing literature analyzes the driving forces of energy consumption and carbon emissions in both developed and developing countries, the studies are still a few on the above issues in developing countries. Some studies pay attention to new emerging countries, such as China and India, but rare studies investigate energy use and carbon emissions in other developing countries, such as the ASEAN countries. Also, a few studies compare the energy consumption and carbon emissions between developed countries and developing countries. This study tries to fill the gap covering all the developed countries and developing countries in the Asia-Pacific countries and aims to illustrate the difference in the trends and drivers of energy consumption and carbon emissions between developed countries and developing countries. The current energy use pattern in developed countries also sheds light on the future energy consumption in developing countries.

3.3 Methodology

This study employs the temporal Index Decomposition Analysis (IDA) to identify the drivers of energy consumption and carbon emissions. The temporal IDA method is a widely

accepted analytical tool adopted by many international organizations.¹¹ This study chooses the multiplicative logarithmic mean Divisia index (M-LMDI) as the decomposition scheme fitting the merits of the desirable method proposed by Ang *et al.* (2002) and Ang (2004). Advantages of the M-LMDI scheme include that (a) it passes the time-reversal test in which the decomposition results do not depend on the base year; (b) it passes the factor reversal test leading to zero residuals in the decomposition results and a transparent explanation; (c) it is consistent in aggregation making sure the same results at the regional level, no matter which sub-level each country chooses.

This section presents the temporal IDA method decomposing the difference in energy consumption and carbon emissions between two years in a specific country. Section 3.3.1 first presents a temporal IDA method for energy consumption. Section 3.3.2 shows a temporal IDA method for carbon emissions.

3.3.1 Temporal IDA: Energy Consumption

The temporal IDA decomposes the total energy consumption into three factors: activity effect, structural effect, and intensity effect. The activity effect quantifies the economic growth leading to an increase in energy consumption. The structural effect measures the adjustment of economic mix that affects the change of energy use. For example, when an economy shifts from the less energy-intensive sector to the energy-intensive one, it leads to an increase in energy consumption. The intensity effect shows the contribution of technology change to the energy consumption. It means that the energy consumption will decline as the technological progress occurs. Equation (3.1.1) shows the equation of energy decomposition.

¹¹ The organizations adopting the IDA framework include the Office of Energy Efficiency (OEE) in Canada, the Office of Energy Efficiency and Renewable Energy (EERE) in United States, the Energy Efficiency and Conservation Authority (EECA) in New Zealand, and International Energy Agency (IEA).

$$E_i^t = \sum_j E_{i,j}^t = \sum_j Y_i^t \frac{Y_{i,j}^t}{Y_i^t} \frac{E_{i,j}^t}{Y_{i,j}^t} = \sum_j Y_i^t S_{i,j}^t I_{i,j}^t \quad (3.1.1)$$

E_i^t and $E_{i,j}^t$ are the gross energy use in country i in year t , and the energy use in country i , sector j in year t . Y_i^t and $Y_{i,j}^t$ are the value-added in country i in year t , and the value-added in country i , sector j in year t . S_i^t and $S_{i,j}^t$ refer to the share of output in country i in the whole region, and the share of output in sector j in the total output in country i in year t . $I_{i,j}^t$ stands for the energy intensity in country i , sector j in year t . The total energy consumption is decomposed into activity effect, structure effect, and intensity effect as shown in Equation (3.1.2).

$$TE_{tot,i}^t = \frac{E_i^t}{E_i^{t-1}} = TE_{act,i}^t \cdot TE_{str,i}^t \cdot TE_{int,i}^t \quad (3.1.2)$$

$$TE_{act,i}^t = \exp \left[\sum_j w_{i,j}^t \ln \left(\frac{Y_{i,j}^t}{Y_{i,j}^{t-1}} \right) \right] \quad (3.1.3)$$

$$TE_{str,i}^t = \exp \left[\sum_j w_{i,j}^t \ln \left(\frac{S_{i,j}^t}{S_{i,j}^{t-1}} \right) \right] \quad (3.1.4)$$

$$TE_{int,i}^t = \exp \left[\sum_j w_{i,j}^t \ln \left(\frac{I_{i,j}^t}{I_{i,j}^{t-1}} \right) \right] \quad (3.1.5)$$

where

$$w_{i,j}^t = \frac{(E_{i,j}^t - E_{i,j}^{t-1}) / (\ln E_{i,j}^t - \ln E_{i,j}^{t-1})}{(E_i^t - E_i^{t-1}) / (\ln E_i^t - \ln E_i^{t-1})} \quad (3.1.6)$$

$TE_{tot,i}^t$, $TE_{act,i}^t$, $TE_{str,i}^t$, and $TE_{int,i}^t$ refer to temporal indicators of the total effect, activity effect, structure effect, and intensity effect in country i in year t in the temporal analysis of energy use. $w_{i,j}^t$ is the log weight of energy consumption.

3.3.2 Temporal IDA: Carbon Emissions

The temporal IDA method decomposes the carbon emissions into five indicators: activity effect, structure effect, intensity effect, energy mix effect, and emission-factor effect. The definitions of activity effect, structure effect, and intensity effect are similar to the definitions of activity effect, structure effect, and intensity effect presented in the previous subsection. They refer to the impact of economic growth, economic structure adjustment, and energy intensity on energy-related carbon emissions. The energy mix effect measures the contribution of the change in the energy structure to the change of carbon emissions. For example, the carbon emissions can be reduced as energy shifts from carbon-intensive energy (e.g., peats and coke) to less carbon-intensive energy (e.g., gas). The emission-factor effect shows the contribution of the change of emission-factor to the variation of carbon emissions. For example, as the technological change on power generation improves the generation efficiency, the default emission-factor of electricity declines. The decomposition of carbon emissions are shown in Equation (3.2.1).

$$C_i^t = \sum_j \sum_k C_{i,j,k}^t = \sum_j \sum_k Y_i^t \frac{Y_{i,j}^t}{Y_i^t} \frac{E_{i,j}^t}{Y_{i,j}^t} \frac{E_{i,j,k}^t}{E_{i,j}^t} \frac{C_{i,j,k}^t}{E_{i,j,k}^t} = \sum_j \sum_k Y_i^t S_{i,j}^t I_{i,j}^t M_{i,j,k}^t U_{i,j,k}^t \quad (3.2.1)$$

where C_i^t is gross carbon emissions in country i in year t and $C_{i,j,k}^t$ is carbon emissions caused by type k fuel generated in sector j in country i in year t . E_i^t , $E_{i,j}^t$, Y_i^t , $Y_{i,j}^t$, $S_{i,j}^t$, and $I_{i,j}^t$ have the same definitions as they are in the previous subsection. $E_{i,j,k}^t$ refers to the energy use by fuel type k , in country i sector j . $M_{i,j,k}^t$ is the share of energy use by fuel type k in the total energy use in country i sector j . $U_{i,j,k}^t$ stands for the emissions coefficients caused by fuel type k in country i sector j . The change of total carbon emissions between

year t and year $t-1$ is decomposed into activity effect, structure effect, intensity effect, mix effect, and emission-factor effect as shown in Equation (3.2.2). Equation (3.2.3) to equation (3.2.7) present the functions of indices.

$$TC_{tot,i}^t = \frac{C_i^t}{C_i^{t-1}} = TC_{act,i}^t \cdot TC_{str,i}^t \cdot TC_{int,i}^t \cdot TC_{mix,i}^t \cdot TC_{emf,i}^t \quad (3.2.2)$$

$$TC_{act,i}^t = \exp \left[\sum_j \sum_k \tilde{w}_{i,j,k}^t \ln \left(\frac{Y_i^t}{Y_i^{t-1}} \right) \right] \quad (3.2.3)$$

$$TC_{str,i}^t = \exp \left[\sum_j \sum_k \tilde{w}_{i,j,k}^t \ln \left(\frac{S_{i,j}^t}{S_{i,j}^{t-1}} \right) \right] \quad (3.2.4)$$

$$TC_{int,i}^t = \exp \left[\sum_j \sum_k \tilde{w}_{i,j,k}^t \ln \left(\frac{I_{i,j}^t}{I_{i,j}^{t-1}} \right) \right] \quad (3.2.5)$$

$$TC_{mix,i}^t = \exp \left[\sum_j \sum_k \tilde{w}_{i,j,k}^t \ln \left(\frac{M_{i,j,k}^t}{M_{i,j,k}^{t-1}} \right) \right] \quad (3.2.6)$$

$$TC_{emf,i}^t = \exp \left[\sum_j \sum_k \tilde{w}_{i,j,k}^t \ln \left(\frac{U_{i,j,k}^t}{U_{i,j,k}^{t-1}} \right) \right] \quad (3.2.7)$$

where

$$\tilde{w}_{i,j,k}^t = \frac{(C_{i,j,k}^t - C_{i,j,k}^{t-1}) / (\ln C_{i,j,k}^t - \ln C_{i,j,k}^{t-1})}{(C_i^t - C_i^{t-1}) / (\ln C_i^t - \ln C_i^{t-1})} \quad (3.2.8)$$

$TC_{tot,i}^t$, $TC_{act,i}^t$, $TC_{str,i}^t$, $TC_{int,i}^t$, $TC_{mix,i}^t$, and $TC_{emf,i}^t$ refer to the indicators of total effect, activity effect, structure effect, and intensity effect, energy mix effect, carbon emissions coefficients effect in country i in year t in the temporal analysis of carbon emissions. $\tilde{w}_{i,j}^t$ is the log weight of carbon emissions.

3.4 Data

3.4.1 Data Collection

This study collects the value-added data from the UN National Accounts Main Aggregate (UN, 2015). There are three main advantages using this database. First, the quality and authority of the data can be ensured. The database collects the latest available national accounts estimates provided by each country's government. For the countries that do not report to the statistical division directly, the data are supplemented by information gathered from additional correspondence from national publications and other sources. Second, this study uses value-added data in the database avoiding double counting for the intermediate goods. Third, the database covers a long time span from 1970 to 2014 and a wide scope (200 countries and areas) in the world. It guarantees the harmony of the data among different countries in this study.

The energy data are mainly collected from the IEA World Energy Statistics (IEA, 2015). This study also refers to the APEC Energy Statistics (APEC-EWG, 2012) and the local energy statistics. The energy data used in this study have several advantages as follows. First, the IEA database covers all the APEC countries and a long time span from 1990 to 2010 ensuring the harmony across different counties within the APEC area. Second, the IEA database contains fuel mix statistics in a high-resolution ensuring an accurate analysis of the energy-related carbon emissions. Third, this study makes an estimation referring to the APEC Energy Statistics and the local energy statistical yearbooks for some developing countries. The adjustment provides consistent and accurate time series data.

The emission-factors are from the IPCC Emission-factor Database (IPCC, 1996). This study uses default emission-factors with an assumption that the fuels are fully combusted. The emission-factors of electricity are estimated based on the main activity use and the default

emission-factors of fuels. Thus, the emission-factors of electricity vary across different countries and different years.

The value added data are in the unit of constant 2005 prices in US dollars to ensure the comparability across different countries in any year. The value added data and the energy consumption data contain four sectors: agriculture sector, industry sector, transport sector, and commercial and other services sector. The energy consumption data are in the unit of thousand tonnes of oil equivalent (ktoe). The emission-factors are in the unit of kg of greenhouse gas per TJ, which are converted to tonnes of greenhouse gas per ktoe. The fuels include 13 types: coal and coal products, peat and peat products, crude NGL and feedstocks, oil products, natural gas, nuclear, hydro, geothermal, solar/wind/others, biofuels and waste, heat production from non-specified combustible fuels, electricity, heat.

3.4.2 Descriptive Analysis

This sub-section presents a descriptive analysis for economic growth, economic structure, and energy structure in the APEC region. Figure 3.1 shows the output by sector in the APEC-17 countries, which provides the economic growth and the economic structure in the region. The total economy contains four sectors: industry sector, transport sector, agriculture sector, and commercial and other services sector. The stacked columns present the share of each sector in the total economy while the trend lines show the output trends, where the initial yield in each sector is normalized as 1. The key findings are listed as follows. First, the average annual economic growth of the overall economy in the APEC-17 countries is 2.8% from 1990 to 2010. Second, the commercial and services sector bears largest output in the APEC-17 region accounting for 62.2% of total economy on average from 1990 to 2010. Industry sector has the second largest output, which is 27.6% on average over the twenty years. Second, the overall economic structure is quite stable from 1990 to 2010. The economic structure adjustment is very mild within the whole APEC-17 region. Third, the

growth rates across different sectors are less heterogeneous, which makes the economic structure steady.

Figure 3.1 Output by Sector in the APEC-17 Region

Figure 3.2 presents the energy structure in the APEC-17 region. The energy consumption is summarized in 6 fuel types: coal products, oil products, natural gas, electricity, bio-waste, and renewable energy. The stacked column is the share of each fuel in the total energy consumption. The trend lines show the changes of fuel, where the initial values are normalized as 1. The key findings are as follows. First, oil products have the largest share (48.0% on average) in the total energy consumption followed by coal products (18.7% on average), and electricity (17.7% on average). Second, the share of oil products and the share of natural gas were quite stable from 1990 to 2000, while they kept declining from 2000 to 2010. The share of electricity and renewable energy kept increasing from 1990 to 2010. Third, the energy consumption is largely heterogeneous among different fuel types. The renewable energy keeps increasing at the rate of 7.5% average annually, while natural gas grows at the rate of 1.6% average annually. The coal products increased fast from 2000 to 2010. Fourth, the energy consumption shifts towards the less carbon-intensive energy (e.g.

renewable energy) and high-efficient energy (electricity) in the APEC-17 over the twenty years.

Figure 3.2 Energy Consumption by Fuel in the APEC-17 Region

3.5 Results

This section presents the temporal decomposition results of energy consumption and carbon emissions. Section 3.5.1 and 3.5.2 discuss the temporal results of energy consumption and carbon emissions in nine developed countries in the APEC region. Section 3.5.3 and section 0 discuss the temporal results of energy consumption and carbon emissions in eight developing countries in the APEC region.

3.5.1 Energy Consumption: Nine Developed Countries in the APEC Region

Figure 3.3 presents the temporal decomposition results of energy consumption in nine developed countries in the APEC region. The difference in energy consumption between year t and the year $t-1$ in a specific country is decomposed into three effects: activity effect, structure effect, and intensity effect. Figure 3.3 shows that Australia, Canada, New Zealand, and the United States have similar patterns in energy consumption. The cumulative total

energy effect is 1.36 in Australia, 1.16 in Canada, 1.32 in New Zealand, and 1.14 in the US over twenty years from 1990 to 2010. It means that energy consumption increases by 36% in Australia, 16% in Canada, 32% in New Zealand, and 14% in the US over twenty years. The highest energy consumption is achieved in 2007 in Canada and US. After 2007, the energy consumption drops due to the global financial crisis. Australia reaches the highest point in 2008 meaning that the financial crisis affects Australia one year later than US and Canada. Activity effect is the main driver for the increase of energy consumption in these four countries, which is consistent with the business cycle. The intensity effect drops significantly in Australia (0.67), Canada (0.72), New Zealand (0.74) and US (0.66) compared to that in other developed countries from 1990 to 2010. The structure effect remains unchanged in Canada, while the structure effect increases slightly in Australia, New Zealand, and the US.

Apart from these four countries, Chile, Korea, and Singapore have similar energy use patterns. The total effect is 2.48 in Chile, 2.20 in Korea, and 3.29 in Singapore. The activity effect almost shapes the total energy effect in these three countries. Korea and Singapore experience the Asian financial crisis that hurts the economic growth and further reduces the energy consumption in these two countries in 1997. The structure effect and intensity effect are mild in both Chile and Singapore. The structure effect slightly drives up the energy consumption while the intensity effect pulls down the total effect moderately from

Figure 3.3 Temporal Decomposition Results of Energy Consumption in Nine Developed Countries in the APEC Region

1990 to 2010. The structure effect in Korea is also mild while the intensity effect significantly lowers the energy consumption in Korea, which is different from Chile and Singapore.

Total energy consumption changes moderately in Japan from 1990 to 2010. The activity effect is mild due to the stagnated economy in Japan over twenty years. The intensity effect slightly reduces the energy consumption in Japan. In Hong Kong, the key factor is intensity effect that shapes the total energy effect. The intensity effect in Hong Kong experiences a large increase in the Asian financial crisis and then drops to the normal level. The activity effect keeps driving up the energy consumption except 1998 and 2009 attributed to the financial crisis. The structure effect shows that the economy in Hong Kong adjusts towards the less energy-intensive sector, such as commercial and services sector, over twenty years.

3.5.2 Carbon Emissions: Nine Developed Countries in the APEC Region

Figure 3.4 shows the temporal decomposition results of carbon emissions in nine developed countries in the APEC region. The difference in carbon emissions between year t and year $t-1$ is decomposed into five indices: activity effect, structure effect, intensity effect, mix effect, and emission-factor effect. The total effect of carbon emissions has a similar trend to the total effect of energy consumption over twenty years in most developed countries in the APEC region except Korea and Singapore. The increase in carbon emissions is more than the increase in energy consumption from 1990 to 2010 in Korea, which means that the energy use pattern becomes more carbon-intensive in Korea. In contrast, the case in Singapore runs the opposite way.

In the temporal results of carbon emissions, activity effect, structure effect, and intensity effect have similar patterns to those effects in the temporal results of energy consumption. Thus, the following illustration focuses on mix effect and emission-factor effect. Although

Figure 3.4 Temporal Decomposition Results of Carbon Emissions in Nine Developed Countries in the APEC Region

the magnitude of these two effects is relatively mild than other three effects, these two effects can still shed light on the impact of energy structure change on carbon emissions. If the mix effect is lower than 1.00, it means that the mix effect has a negative contribution to the change of carbon emissions. In this case, the energy consumption shifts towards less carbon-intensive fuels, such as natural gas and liquid natural gas. If the emission-factor effect is lower than 1.00, it indicates that the electricity generation process tends to use less carbon-intensive energy.

The mix effect and the emission-factor effect fluctuate around 1.00 moderately over twenty years in Australia, Canada, Japan, and New Zealand. It means that the fuel structure remains stable and that the fuel mix in the electricity generation sector almost remains unchanged from 1990 to 2010 in above countries. The mix effect drops over years in Chile meaning that the energy consumption shifts to the less carbon-intensive fuels in Chile. The emission-factor effect reduces significantly in Hong Kong (0.92 by 2010) and Singapore (0.73 by 2010) indicating the electricity sector tends to use less carbon-intensive fuels in these two countries. In contrast, the fuel mix pattern runs in the opposite way in Korea. Both mix effect and emission-factor effect push up the energy-related carbon emissions greatly. The mix effect is 1.10 by 2010 in Korea. The emission-factor effect is 1.12 by 2010 in Korea. It means that Korea tends to use more carbon-intensive fuels in production and electricity generation. For the US, the mix effect leads to an increase in carbon emissions, while the emission-factor effect offsets the increase in carbon emission. It indicates that the energy structure in the US tends to be more carbon-intensive, while the electricity generation sector becomes less carbon-intensive. The temporal results also show that the economic crisis does not affect mix effect and emission-factor effect in nine developed countries.

3.5.3 Energy Consumption: Eight Developing Countries in the APEC Region

Figure 3.5 shows the temporal decomposition results of the energy consumption in eight developing countries in the APEC region. The difference in energy consumption between year t and year $t-1$ is decomposed into three factors: activity effect, structure effect, and intensity effect. Please note that the vertical legends of Figure 3.5 (a) and (h) are different from the vertical legends of the rest of figures due to a rapid increase in energy consumption in China and Vietnam.

In general, energy consumption increases fast in eight developing countries in the APEC region from 1990 to 2010. The growth rates of energy consumption in eight developing countries are much higher than those in nine developed countries. The cumulative total effect of energy consumption is 3.34 in China, 3.09 in Indonesia, 3.13 in Malaysia, and 7.76 in Vietnam by 2010. Activity effect plays a key role for the increase in energy consumption in eight developing countries in the APEC region due to a rapid economic growth from 1990 to 2010. The economic shocks (e.g. the 1997 Asian financial crisis and 2008 global crisis) affect the energy consumption in eight developing countries significantly through the channel of activity effect. In contrast to nine developed countries, intensity effect does not drop significantly in most developing countries of this region except China and Philippines. The intensity effect even increases over years in Vietnam. Numerically, the intensity effect is 1.51 in Vietnam, 0.97 in Indonesia, 0.93 in Malaysia, 0.91 in Peru, 0.79 in Thailand, 0.71 in Mexico, 0.66 in Philippines, and 0.36 in China by 2010. The structure effect drives up the energy consumption from 1990 to 2010 in eight developing countries in this region. It indicates that the economy shifts to energy-intensive sectors, such as industry sector, in eight developing countries. The structure effect in eight developing countries is higher than that

Figure 3.5 Temporal Decomposition Results of Energy Consumption in Eight Developing Countries in the APEC Region

in nine developed countries indicating the economies of eight developing countries shift more to the energy intensive sector than the economies of nine developed countries.

3.5.4 Carbon Emissions: Eight Developing Countries in the APEC Region

Figure 3.6 presents the temporal decomposition results of carbon emissions in eight developing countries of the APEC region. The difference in carbon emissions between year t and year $t-1$ is decomposed into five effects: activity effect, structure effect, intensity effect, mix effect, and emission-factor effect. Please note that the vertical legends of Figure 3.6 (a), (c), and (h) are different from the vertical legends of the rest of figures due to a rapid increase of carbon emissions in China, Malaysia, and Vietnam.

The total effect of energy-related carbon emissions has a similar trend to the total effect of energy consumption in most developing countries in the APEC region. The energy-related carbon emissions increase much more rapidly over twenty years in eight developing countries than those in nine developed countries. The possible reason is that most developed countries implement an environmental policy to reduce the GHGs while developing countries do not commit to the carbon reduction. Activity effect, structure effect, and intensity effect in the decomposition of carbon emissions have similar values as those indicators in the decomposition of energy consumption. Unlike developed countries, intensity effect does not contribute much to the carbon reduction in developing countries. The following discussion focuses on mix effect and emission-factor effect, which shows the contribution of the change of energy structure to carbon emissions.

Figure 3.6 Temporal Decomposition Results of Carbon Emissions in Eight Developing Countries in the APEC Region

Both mix effect and emission-factor effect vary around 1.00 mildly in Indonesia, Malaysia, and Thailand. It means that the energy structure almost does not change over twenty years from 1990 to 2010 in the above countries. China and Vietnam have the similar pattern of the change of energy structure. The mix effect drives up carbon emissions while emission-factor effect lowers the carbon emissions in China and Vietnam. It indicates that the energy consumption shifts towards more carbon-intensive fuels, while the electricity generation tends to use less carbon-intensive fuels in these two countries. In Mexico, the mix effect keeps going up over twenty years meaning that the energy consumption shifts towards carbon-intensive fuels. In Peru, the emission-factor effect goes up from 2004 to 2010 meaning that the electricity generation process tends to use more carbon-intensive fuels than other countries. In Philippines, both mix effect and emission-factor effect pull up the carbon emissions indicating that the energy structure and electricity generation shift to more carbon-intensive fuels. The temporal results also show that the economic crisis does not affect mix effect and emission-factor effect in eight developing countries.

3.6 Conclusions

This study aims to investigate the trends and drivers of energy consumption and carbon emissions in 17 APEC countries over twenty years from 1990 to 2010. The study uses the temporal IDA model to identify the drivers for the change of energy consumption and carbon emissions in each country. The APEC countries are categorized into two groups: nine developed countries and eight developing countries. The analysis specifies the key factors regarding energy consumption and carbon emissions in nine developed countries and eight developing countries in the APEC region. There are three main contributions in this study. First, the study identifies the impact of three factors (activity effect, structure effect, and intensity effect) on the energy consumption in APEC-17 countries. Second, the study measures the contributions of five factors (activity effect, structure effect, intensity effect,

mix effect, and coefficient factor effect) to carbon emissions in APEC-17 countries. Third, the study explores the change of energy consumption and carbon emissions when economy experiences a recession period. The negative macroeconomic events include the 1997 Asian Financial Crisis and the 2008 Global Financial Crisis. The details of the conclusions are summarized as follows.

First, the temporal IDA model analyzes the drivers of the change of energy consumption including activity effect, structure effect, and intensity effect. The activity effect is a key factor of the increase of energy consumption in eight developing countries, while the impact of activity effect on the energy consumption is relatively small in nine developed countries. It means that a rapid economic growth drives up the energy consumption over twenty years in most developing countries of the APEC region. The intensity effect is an important factor that lowers the energy consumption in developed countries, while it almost remains unchanged in developing countries, except China. It means that the energy efficiency improves in the developed countries, while the energy technological progress does not occur in most developing countries. The structure effect leads to an increase in energy consumption and carbon emissions in eight developing countries indicating that the developing countries shift their economy to the energy-intensive sector, such as industry sector. The structure effect is not significant in developed countries.

Second, the temporal IDA model decomposes energy-related carbon emissions into five factors: activity effect, structure effect, intensity effect, mix effect, and emission-factor effect. The activity effect, structure effect, and intensity effect in the emission analysis have similar trends as these indicators in the energy consumption analysis. The mix effect and emission-factor effect show the change of energy structure, which are relatively mild compared to activity effect and intensity effect. The mix effect and emission-factor effect almost remains unchanged in some developed countries and developing countries, such as

Australia, Canada, Japan, Malaysia, New Zealand, and Thailand. In contrast, mix effect or emission-factor effect keeps going up over twenty years in some emerging countries, such as Korea, China, and Vietnam. It indicates that the fuels used in production shifts towards to carbon-intensive fuels, as well as, that the power plants tend to produce more by-products, CO₂, in the process of electricity generation.

Third, this study investigates the change of energy consumption and carbon emissions given a negative macroeconomic shock and corresponding drivers behind the changes. The results show that the shock of financial crisis only affects the activity effect that is the main driver of energy consumption and carbon emissions. Thus, the negative shock of macroeconomics can lead to less increase of energy consumption and carbon emissions in most countries of the APEC region. Although the extreme macroeconomic events influence the activity effect significantly, they have little impact on the structure effect, intensity effect, mix effect, and emission-factor effect. It means that economic shock hardly influences the change of economic structure, energy structure, and energy efficiency in the short-run. The economic shock only has an impact on the economic growth, through this channel to affect the energy consumption and carbon emissions.

4 Essay 3: Energy Intensity and Carbon Intensity in the APEC-17 Countries: Gaps and Drivers

4.1 Introduction

Convergence in macroeconomic indicators such as the rate of economic growth has been one of the key questions among development economists. Convergence has many economic implications such as the convergence in the rate of economic growth between poorer and richer countries indicates that there has been an improvement in the level of standard living of the poorer countries. Similar to economic convergence, a tendency of the convergence in energy intensity and carbon intensity could have meaningful economic and energy-related implications. A convergent tendency indicates that countries with high energy and carbon intensity and countries with low energy and carbon intensity tend to have a common energy use pattern. It also implies that countries with a lagging energy technology can catch up with the technology leaders. From the perspective of policy implications, a convergent trend supports that it is possible to achieve a stringent carbon target for the countries with high carbon intensity. If there is a convergent trend or a divergent trend, the ensuing question is which factors lead to such a trend. Possible explanations include the convergent or divergent pattern in economic growth, economic structure, energy efficiency, fuel structure, and the efficient factors. To identify the key driver among these possible factors could deserve a further study. An institutional perspective poses another question that whether the economic openness and regional cooperation promote the convergence of energy and carbon intensity. To analyze whether the economic cooperation is effective to narrow down the gap of energy and carbon intensity among the member countries is another deserving question to be answered.

Many studies explore the trends of energy intensity and energy-related carbon intensity in a single country. Most of them employ a temporal Index Decomposition Analysis (IDA) that decomposes the difference of energy intensity or carbon intensity between two years within a country. Although they use a common method, the results of different single-country studies cannot be used to compare directly and to examine the convergent tendency of energy intensity and CO₂ intensity among different countries. First, the indices of energy intensity and carbon intensity are monetary based. Different local currency systems lead to difficulties in comparing the indicators of energy intensity and carbon intensity. Second, the decomposition results are different due to the sub-sectors at a high-resolution level or a low-resolution level (Ma and Stern (2008)). The difference in categorizing sub-sectors could cause incapability of comparing the results of single-country studies.

Multi-country energy database that has been accessible recently enables some regional studies to explore the pattern of energy intensity and carbon intensity among different countries in a region. Some of the regional studies are in the framework of temporal IDA, which allows observing the factors that affect the development patterns of energy intensity or carbon intensity across countries. However, such a method cannot directly address the discrepancy across countries and to reflect the trends of the absolute difference in energy intensity and carbon intensity among different countries over years. Some of the regional studies employ the spatial regression method to examine the β -convergence of energy intensity (Markandya *et al.*, 2006; Mulder and de Groot, 2012; Wan *et al.*, 2015).¹² These studies show whether the convergent trend exists in a region, but they do not explore the key factors leading to the convergent pattern of energy and carbon intensity.

¹² β -convergence of energy intensity refers to the country with high initial level of energy intensity tending to reduce the energy intensity fast.

Upon noticing the limitations of methodology, this study employs a spatial IDA method to analyze whether there is a convergent pattern in sub-regions and to examine the factors that affect the absolute difference in energy intensity and carbon intensity across the APEC countries. The spatial IDA method decomposes the difference of energy intensity and carbon intensity between a specific country and the average level of the region in a particular year. The data in five years are analyzed including 1990, 1995, 2000, 2005, and 2010. This method has two advantages. First, it allows a direct comparison among countries in a specific year. It enables examining the discrepancy across countries over years. The trends give an implication whether the countries with high energy and carbon intensity could catch up the countries with low energy and carbon intensity. Second, the spatial IDA method provides the factors that affect the convergent trend or the divergent trend. Examining the key drivers also sheds light on the policy implications how to narrow down the discrepancy in a region.

There are two key interests in this study. First, as an extension of the previous chapter, this study is interested in the difference between developed countries and developing countries continuously. The study examines whether there is a convergent tendency in energy intensity and carbon intensity a) within developed countries, b) within developing countries, and c) between the average level of developed countries and developing countries over years and what are the key influencing factors. Second, there is several overlapping regional cooperation within the APEC region including the North American Free Trade Agreement (NAFTA), the Association of Southeast Asian Nations (ASEAN), and the ASEAN Plus Three (APT) cooperation. This study aims to analyze whether the economic cooperation helps narrow down the gap of energy intensity and carbon intensity among member countries and whether the economic cooperation promotes the energy technological diffusion in the cooperation area. The findings point out which regional policies help enhance the convergence of energy and carbon intensity among the member countries.

The remaining essay is organized as follows. Section 4.2 summarizes the existing literature from the perspective of methodology and application. Section 4.3 presents the spatial IDA model and introduces the database used in the study. Section 4.4 shows the results of two key questions: a) the discrepancy of energy intensity and carbon intensity between developed countries and developing countries, b) the difference in energy intensity and carbon intensity among the member countries in an economic cooperation organization. Section 4.5 concludes the study.

4.2 Literature Review

4.2.1 A Methodology Review: Spatial IDA

The spatial IDA method has a short history, which is first proposed in Ang and Zhang (1999) to conduct inter-regional comparisons and to explore the driving force of the difference of carbon emissions in three OECD regions and three world regions. The spatial IDA method decomposes the difference of carbon emissions between two regions in a specific year. It directly captures the factors contributing to the absolute difference. The spatial IDA in Ang and Zhang (1999) is a bilateral regional (B-R) model for the comparison between only two regions. The bilateral regional model has to set several groups to conduct the multi-region analysis.

As the scope extends to multiple regions, the bilateral regional model is not convenient for analysis. Two modified spatial IDA methods are developed for the multi-region studies. Sun (2000) chooses a specific country as a benchmark and then decomposes the difference in the carbon intensity between each country and the benchmark country. This modified spatial IDA only focuses on the benchmark country and shows the comparison results between benchmark country and another specific country in the region. One limitation is that it cannot illustrate the difference between a set of any two countries in the region. Schipper *et al.*

(2001) proposes a modified spatial IDA method that decomposes the difference between a specific country and the average level of the rest of countries in the region. This method enables comparing each country with the rest of countries, but the drawback is that it cannot present the comparison of any two countries directly.

Ang *et al.* (2015) proposes a radial-regional (R-R) spatial decomposition analysis model. This method decomposes the difference in the energy consumption between a specific country and the average level of all the countries in the region. Each country is compared to the radial value that is the average level of the region. The R-R spatial decomposition analysis model allows comparing the performance of any two countries indirectly after the comparison results between a country and the average level of the region have been gotten.

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4.2.2 An Application Review: Regional Analysis

The regional studies on energy consumption, energy intensity, carbon emissions, and carbon intensity are mainly from two approaches: a temporal IDA approach and a spatial IDA approach.

The regional studies from the temporal IDA approach first decompose the difference in energy consumption or carbon emissions over two years within each country and then compare the trends of energy consumption or carbon emissions based on the temporal IDA results in each country. Many studies examine the energy consumption or carbon emissions in the European Union (EU) from a regional approach, a national approach, and a sector approach. Löschel *et al.* (2015) shows that the sectoral intensity effect significantly lowers the energy intensity in the EU-27 countries, and that the economy in the EU-27 shifts

¹³ The indirect results conducted by the R-R model are not equal to the direct decomposition results in the B-R model.

towards the energy-intensive countries. Fernández González *et al.* (2014) explores the EU-27 from a national approach, which indicates that the sectoral intensity effect partially lowers the energy intensity offset by the activity effect in the EU-27 countries and that the trends of energy intensity are heterogeneous between the Mediterranean countries and the rest of the EU-27. Other studies of EU focus on the impact of electricity and renewable energy on the carbon emissions, which shows that the reduction of carbon emissions is resulting from using less carbon-intensive energy, such as gas and renewable energy (Fernández González *et al.*, 2014; Moutinho *et al.*, 2015). Mendiluce *et al.* (2010) compares the evolution of energy intensity in Spain and the EU-15. It shows that the boom in the construction sector and the transport sector is the key driving force of the divergence of Spain to other EU-15 countries while the household demand is a factor that makes convergence of Spain to the EU-15. Mulder and de Groot (2012) and Mulder *et al.* (2014) investigate the energy intensity development in OECD-18. The results present the evidence that there is a convergent trend of energy intensity in the OECD-18 mainly caused by the convergence of within-sector energy intensity levels. A few studies use the temporal IDA method to explore the energy intensity in the non-OECD countries. Jimenez and Mercado (2014) studies the energy intensity in the Latin American countries showing that the change of energy intensity is mainly driven by the improvement in energy efficiency. Wang (2013) examines the energy intensity in the world and points the contribution of technological progress to the reduction of energy intensity.

Some studies make a comparison among countries within a region using the spatial IDA method. Ang and Zhang (1999) compares the carbon emissions among the North American (NA) region, the European Union (EU), and the Pacific Area (PA), and among the OECD countries, the former Soviet Union and Central and Eastern Europe (FSU/CEE), and the rest of the world (ROW). The results identify the difference in carbon emissions among regions

mainly caused by the difference in energy intensity, income level, and population. Sun (2000) compares the difference in carbon intensity between France and the rest of the EU-15, which is attributed to the difference in the share of fossil fuels use in the total energy consumption. Schipper *et al.* (2001) analyzes the difference in the carbon intensity among the IEA member countries and shows that transport activity levels, energy intensities, and utility carbon intensity share can equally explain the differences among countries. Lee and Oh (2006) investigates the difference in carbon emissions among the high-income countries, the middle-income countries, and the low-income countries within the APEC countries, and finds that the income gap and population gap lead to the difference. Bataille *et al.* (2007) makes a comparison of carbon intensity among the G7 countries indicating that the key drivers of difference are inflexible characters, such as climate factor and geography factor.

In the existing regional studies, most studies focus on developed areas, such as the EU countries and the OECD countries. A few studies examine developing regions, such as the Latin American countries. Due to the unavailability to the energy data in developing countries, rare studies explain the gap of energy intensity and carbon intensity between developed countries and developing countries. This study tries to overcome this limitation in the existing study. Apart from this point, the study further explores whether regional cooperation can narrow down the gap within a region. If the answer is yes, how does the catching-up process happen? Which factors mainly cause the catching-up process?

4.3 Methodology and Data

4.3.1 Spatial IDA: Energy Intensity

This study employs the spatial IDA to investigate the difference in energy intensity between a specific country and the average level of the group. The baseline is the arithmetic average of the corresponding values, which provides a reference to compare the difference among

multiple countries in a region. The energy intensity in a specific country deviates from the average level due to a) the difference in economic structure (structure effect), and b) the difference in sectoral energy intensity (intensity effect). For example, if the economy in a specific country focuses more on energy-intensive sectors, the feature of economic structure results in a positive deviation compared to the average level of energy intensity. The difference in sectoral energy intensity also contributes to the deviation of energy intensity. Equation (4.1.1a) and Equation (4.1.1b) present the decomposition equations for country i and the average level in the region.

$$I_i^t = \sum_j \frac{Y_{i,j}^t}{Y_i^t} \frac{E_{i,j}^t}{Y_{i,j}^t} = \sum_j S_{i,j}^t I_{i,j}^t \quad (4.1.1a)$$

$$\bar{I}^t = \sum_j \frac{\bar{Y}_j^t}{\bar{Y}^t} \frac{\bar{E}_j^t}{\bar{Y}_j^t} = \sum_j \bar{S}_j^t \bar{I}_j^t \quad (4.1.1b)$$

where I_i^t , $I_{i,j}^t$, $\bar{I}^t$, and $\bar{I}_j^t$ are the energy intensity in country i in year t , the energy intensity in country i sector j year t , the average energy intensity in the region in year t , and the average energy intensity in sector j across different countries in the region in year t . Y_i^t , $Y_{i,j}^t$, $\bar{Y}^t$, and $\bar{Y}_j^t$ represent the output in country i in year t , the output in country i sector j year t , the average output in the region in year t , and the average output in sector j across different countries in the region in year t . $E_{i,j}^t$ and $\bar{E}_j^t$ are the energy use in country i sector j in year t , and the average energy consumption in sector j in the region in year t . $S_{i,j}^t$ and $\bar{S}_j^t$ are the share of the output in sector j in the total economy in country i in year t , and the share of the overall output in sector j in the total economy in this region in year t .

The difference in energy intensity between a specific country and the average level is attributed to structural effect and intensity effect as shown in Equation (4.1.2). Equation (4.1.3) and Equation (4.1.4) show the equation of structure effect and intensity effect.

$$SE_{tot,i}^t = \frac{I_i^t}{\bar{I}^t} = SE_{str,i}^t \cdot SE_{int,i}^t \quad (4.1.2)$$

$$SE_{str,i}^t = \exp \left[\sum_j \bar{w}_{i,j}^t \ln \left(\frac{S_{i,j}^t}{\bar{S}_j^t} \right) \right] \quad (4.1.3)$$

$$SE_{int,i}^t = \exp \left[\sum_j \bar{w}_{i,j}^t \ln \left(\frac{I_{i,j}^t}{\bar{I}_j^t} \right) \right] \quad (4.1.4)$$

Where

$$\bar{w}_{i,j}^t = \frac{\left(\frac{E_{i,j}^t}{E_i^t} - \frac{\bar{E}_j^t}{\bar{E}^t} \right) / \left(\ln \frac{E_{i,j}^t}{E_i^t} - \ln \frac{\bar{E}_j^t}{\bar{E}^t} \right)}{\sum_j \left(\frac{E_{i,j}^t}{E_i^t} - \frac{\bar{E}_j^t}{\bar{E}^t} \right) / \left(\ln \frac{E_{i,j}^t}{E_i^t} - \ln \frac{\bar{E}_j^t}{\bar{E}^t} \right)} \quad (4.1.5)$$

where $E_i^t, \bar{E}^t$ refer to the gross energy use in country i in year t , and the average energy use in the region in year t . $SE_{tot,i}^t, SE_{str,i}^t, SE_{int,i}^t$ are the spatial indicators of energy intensity for total effect, structure effect, and energy intensity effect in country i compared to the average level in the region in a specific year t . $\bar{w}_{i,j}^t$ is the weight.

4.3.2 Spatial IDA: Carbon Intensity

The spatial IDA method explores the difference in the carbon intensity between a specific country and the average level in a region. The carbon intensity in each country is compared to the average level in the region. The spatial IDA method looks for the key drivers leading

to the deviation of carbon intensity in each country from the average level. The carbon intensity negatively deviates from the average level due to a) the difference of economic structure (structure effect), b) the difference of sectoral energy intensity (intensity effect), c) the difference of energy structure (mix effect), and d) the difference of emission-factor (emission-factor effect). For example, if the economy in a specific country focuses more on carbon-intensive sectors, this feature of economic structure leads to a high carbon-intensity compared to the average level. High sectoral energy intensity also results in a high carbon-intensity. If the economy in a specific country uses more carbon-intensive fuels, such as coals and peats, the feature of energy structure contributes to a high level of carbon intensity compared to the average level. Last, a high emission-factor in a particular country also leads to a high level of carbon intensity deviated from the average level. Equation (4.2.1a) and equation (4.2.1b) are decomposition equations for country i and the average level in the region.

$$CI_i^t = \sum_j \sum_k \frac{Y_{i,j}^t}{Y_i^t} \frac{E_{i,j}^t}{Y_{i,j}^t} \frac{E_{i,j,k}^t}{E_{i,j}^t} \frac{C_{i,j,k}^t}{E_{i,j,k}^t} = \sum_j \sum_k S_{i,j}^t I_{i,j}^t M_{i,j,k}^t U_{i,j,k}^t \quad (4.2.1a)$$

$$\overline{CI}^t = \sum_j \sum_k \frac{\bar{Y}_j^t}{\bar{Y}^t} \frac{\bar{E}_j^t}{\bar{Y}_j^t} \frac{\bar{E}_{j,k}^t}{\bar{E}_j^t} \frac{\bar{C}_{j,k}^t}{\bar{E}_{j,k}^t} = \sum_j \sum_k \bar{S}_j^t \bar{I}_j^t \bar{M}_{j,k}^t \bar{U}_{j,k}^t \quad (4.2.1b)$$

where CI_i^t and $\overline{CI}^t$ represent the carbon intensity in country i in year t , and the average carbon intensity level in the region in year t . $E_{i,j,k}^t$ and $\bar{E}_{j,k}^t$ are the fuel k used in country i sector j in year t , and the average level of fuel k used in sector j in the region in year t . $C_{i,j,k}^t$ and $\bar{C}_{j,k}^t$ refer to the carbon emissions caused by fuel k used in country i sector j in year t , and the average level of carbon emissions caused by fuel k used in sector j in the region in year t . $M_{i,j,k}^t$ and $\bar{M}_{j,k}^t$ are the share of fuel k in the total energy used in sector j in country i

in year t , and the average share of fuel k in the total energy used in sector j in year t . $U_{i,j,k}^t$

and $\bar{U}_{j,k}^t$ represent the emission-factor of fuel k used in country i sector j in year t , and the

average emission-factor of fuel k used in sector j in year t .

The difference in carbon intensity between a specific country and the average level is decomposed into four factors as shown in Equation (4.2.2). Equation (4.2.3) to Equation (4.2.6) presents the equations of structure effect, intensity effect, mix effect, emission-factor effect, which lead to a deviation of the carbon intensity in a specific country from the average level.

$$SC_{tot,i}^t = \frac{CI_i^t}{\bar{CI}^t} = SC_{str,i}^t \cdot SC_{int,i}^t \cdot SC_{mix,i}^t \cdot SC_{emf,i}^t \quad (4.2.2)$$

$$SC_{str,i}^t = \exp \left[\sum_j \sum_k \bar{w}_{i,j,k}^t \ln \left(\frac{S_{i,j}^t}{\bar{S}_j^t} \right) \right] \quad (4.2.3)$$

$$SC_{int,i}^t = \exp \left[\sum_j \sum_k \bar{w}_{i,j,k}^t \ln \left(\frac{I_{i,j}^t}{\bar{I}_j^t} \right) \right] \quad (4.2.4)$$

$$SC_{mix,i}^t = \exp \left[\sum_j \sum_k \bar{w}_{i,j,k}^t \ln \left(\frac{M_{i,j,k}^t}{\bar{M}_{j,k}^t} \right) \right] \quad (4.2.5)$$

$$SC_{emf,i}^t = \exp \left[\sum_j \sum_k \bar{w}_{i,j,k}^t \ln \left(\frac{U_{i,j,k}^t}{\bar{U}_{j,k}^t} \right) \right] \quad (4.2.6)$$

where

$$\bar{w}_{i,j,k}^t = \frac{\left(\frac{C_{i,j,k}^t}{C_i^t} - \frac{\bar{C}_{j,k}^t}{\bar{C}^t} \right) / \left(\ln \frac{C_{i,j,k}^t}{C_i^t} - \ln \frac{\bar{C}_{j,k}^t}{\bar{C}^t} \right)}{\sum_j \sum_k \left(\frac{C_{i,j,k}^t}{C_i^t} - \frac{\bar{C}_{j,k}^t}{\bar{C}^t} \right) / \left(\ln \frac{C_{i,j,k}^t}{C_i^t} - \ln \frac{\bar{C}_{j,k}^t}{\bar{C}^t} \right)} \quad (4.2.7)$$

where $SC_{tot,i}^t$ is the total carbon intensity effect measuring the deviation of the carbon intensity in country i from the average level in a region in year t . $SC_{str,i}^t$ represents the spatial indicator of structure effect affecting the deviation of carbon intensity in country i in year t . $SC_{int,i}^t$ is the spatial indicator of intensity effect influencing the deviation of carbon intensity in country i in year t . $SC_{mix,i}^t$ is the spatial indicator of mix effect contributing to the deviation of the carbon intensity in country i in year t . $SC_{enf,i}^t$ is the spatial indicator of emission-factor effect affecting the deviation of the carbon intensity in country i in year t . $\bar{w}_{i,j,k}^t$ is the weights for the calculation. C_i^t and $\bar{C}^t$ refer to the total carbon emissions in country i in year t , and the average level of carbon emissions in the region in year t .

4.3.3 Data

This study collects value added data from the UN National Accounts Main Aggregate (UN, 2015) that has three main advantages. First, the database ensures the data quality and authority. It collects the latest available national accounts provided by each country's government. The database also collects data from national statistical offices and from national publications as supplement and reference. Second, this study uses value added data avoiding double counting for the intermediate goods. Third, the database covers a long time span from 1970 to 2014 and a wide scope of 200 countries in the world, which guarantees the harmony of the data in this study.

This study collects the energy data mainly from the IEA World Energy Statistics (IEA, 2015). This study also refers to the APEC Energy Statistics (APEC-EWG, 2012) and the local energy statistical yearbooks. The energy data in this study have several advantages as follows. First, the IEA database covers all APEC countries and a long time span from 1990

to 2010 ensuring the harmony across different countries within the APEC area. Second, the IEA database contains fuel mix statistics in a high-resolution, which makes it possible to make an accurate analysis of energy-related carbon emissions. Third, this study makes an estimation referring to the APEC Energy Statistics and the local energy statistical yearbooks for some developing countries. The adjustment provides consistent and accurate time series data.

The emission-factors are from the IPCC Emission-factor Database (IPCC, 1996). This study uses default emission-factors with an assumption that the fuels are fully combusted. The emission-factors of electricity are estimated based on the main activity use and the default emission-factors of fuels. Thus, the emission-factors of electricity vary across different countries and different years.

The value added data are in the unit of constant 2005 prices in US dollars to ensure the comparability across different countries in any year. The value added data and the energy consumption data contain four sectors: agriculture sector, industry sector, transport sector, and commercial and other services sector. The energy consumption data are in the unit of thousand tonnes of oil equivalent (ktoe). The emission-factors are in the unit of kg of greenhouse gas per TJ, which are converted to tonnes of greenhouse gas per ktoe. The fuels include 13 types: coal and coal products, peat and peat products, crude NGL and feedstocks, oil products, natural gas, nuclear, hydro, geothermal, solar/wind/others, biofuels and waste, heat production from non-specified combustible fuels, electricity, heat.

The data collection is the same as essay 2. Thus, the descriptive analysis does not repeat here.

4.4 Results

4.4.1 Developed Countries and Developing Countries

4.4.1.1 Results within Developed Countries

Table 4.1 presents the spatial results of energy intensity across nine developed countries in the APEC region in 1990, 1995, 2000, 2005, and 2010. The energy intensity in Hong Kong, Japan, and Singapore is much lower than the average level of energy intensity in nine developed countries, while the energy intensity in Canada, Chile, and Korea is much larger than the average level. The leading factor of the difference in energy intensity is intensity effect. The results also suggest that there is not a clear convergent trend in developed countries over years. The variance of total effect is quite stable over years meaning that the diversity of energy intensity across different countries does not change much from 1990 to 2010. From the perspective of each country, Australia and the United States are two countries with the energy intensity above the average level and with a declined trend of total effects. The energy intensity in Japan is below the average level and has a climbing trend over years. It indicates that the energy intensity in Australia, Japan, and the United States converges to the average level over the twenty years. In contrast, Chile runs in the opposite way, which becomes far away from the average level.

Table 4.1 Spatial Decomposition Results of Energy Intensity within Nine Developed Countries in the APEC Region

	AUS	CAN	CHL	HKG	JPN	ROK	NZL	SGP	USA	variance
Panel A: Year 1990										
$SE_{str,i}^t$	1.12	1.05	1.15	1.12	1.15	0.95	1.06	1.38	0.91	0.0161
$SE_{int,i}^t$	0.99	1.54	1.20	0.40	0.52	1.39	1.13	0.43	1.22	0.1611
$SE_{tot,i}^t$	1.11	1.61	1.38	0.45	0.60	1.31	1.20	0.60	1.11	0.1440
Panel B: Year 1995										
$SE_{str,i}^t$	1.13	1.03	1.17	1.02	1.10	0.94	1.12	1.36	0.94	0.0148
$SE_{int,i}^t$	0.94	1.63	1.24	0.45	0.57	1.71	1.10	0.38	1.15	0.2065
$SE_{tot,i}^t$	1.06	1.67	1.45	0.46	0.62	1.61	1.23	0.51	1.08	0.1893

Panel C: Year 2000										
$SE_{str,i}^t$	1.11	1.05	1.26	1.01	1.11	1.09	1.12	1.37	0.93	0.0153
$SE_{int,i}^t$	0.93	1.50	1.23	0.59	0.58	1.37	1.10	0.42	1.14	0.1279
$SE_{tot,i}^t$	1.03	1.58	1.56	0.60	0.64	1.49	1.23	0.58	1.06	0.1503
Panel D: Year 2005										
$SE_{str,i}^t$	1.09	1.01	1.22	0.91	1.11	1.11	1.10	1.33	0.93	0.0150
$SE_{int,i}^t$	0.92	1.55	1.28	0.46	0.60	1.23	1.09	0.50	1.12	0.1291
$SE_{tot,i}^t$	1.00	1.57	1.56	0.42	0.67	1.37	1.20	0.66	1.05	0.1505
Panel E: Year 2010										
$SE_{str,i}^t$	1.08	0.97	1.15	0.83	1.11	1.10	1.08	1.26	0.94	0.0144
$SE_{int,i}^t$	0.91	1.54	1.47	0.50	0.60	1.17	1.13	0.57	1.12	0.1310
$SE_{tot,i}^t$	0.99	1.50	1.69	0.41	0.66	1.29	1.21	0.72	1.06	0.1519

Table 4.2 shows the results of the difference in carbon intensity between a particular developed country and the average level of nine developed countries in the APEC in 1990, 1995, 2000, 2005, and 2010. The trend of carbon intensity is similar to the trend of energy intensity. Japan and Hong Kong are two countries (or special administrative region) with the lowest carbon intensity, while Chile and Korea are the two countries with the highest carbon intensity. The key effect causing the difference in carbon intensity among nine developed countries is intensity effect followed by emission-factor effect. Structure effect and mix effect are minor factors leading to the difference. Japan, Hong Kong, and Singapore are three countries with the lowest intensity effect, while Canada, Chile, and Korea are three countries with the highest intensity effect. The change of the difference in carbon intensity among nine developed countries does not show a clear convergent or divergent tendency over twenty years from 1990 to 2010. Table 4.1 and Table 4.2 show that the variance of energy intensity is larger than the variance of carbon intensity in 1990, 1995, 2000, 2005, and 2010. It suggests that the difference in energy intensity across nine developed countries is larger than the difference in carbon intensity indicating that the country with a high energy consumption use less carbon-intensive energy, namely clean energy.

Table 4.2 Spatial Decomposition Results of Carbon Intensity within Nine Developed Countries in the APEC Region

	AUS	CAN	CHL	HKG	JPN	ROK	NZL	SGP	USA	variance
Panel A: Year 1990										
$SC_{str,i}^t$	1.11	1.05	1.18	1.08	1.14	0.96	1.06	1.29	0.92	0.0110
$SC_{int,i}^t$	0.96	1.54	1.19	0.45	0.54	1.38	1.14	0.47	1.19	0.1472
$SC_{mix,i}^t$	1.05	0.99	1.03	1.12	1.04	1.00	1.00	1.17	0.99	0.0037
$SC_{enf,i}^t$	1.17	0.80	0.98	1.27	0.93	0.90	0.75	1.26	1.04	0.0318
$SC_{tot,i}^t$	1.32	1.28	1.42	0.69	0.59	1.19	0.90	0.89	1.13	0.0744
Panel B: Year 1995										
$SC_{str,i}^t$	1.11	1.03	1.19	0.99	1.09	0.97	1.12	1.27	0.94	0.0101
$SC_{int,i}^t$	0.93	1.63	1.24	0.51	0.58	1.71	1.11	0.40	1.12	0.1957
$SC_{mix,i}^t$	1.04	1.00	1.05	1.10	1.04	0.98	1.02	1.24	0.99	0.0055
$SC_{enf,i}^t$	1.18	0.78	0.86	1.28	0.91	0.95	0.72	1.32	1.05	0.0413
$SC_{tot,i}^t$	1.27	1.30	1.34	0.71	0.60	1.54	0.91	0.82	1.11	0.0908
Panel C: Year 2000										
$SC_{str,i}^t$	1.09	1.06	1.28	1.01	1.10	1.10	1.12	1.29	0.94	0.0114
$SC_{int,i}^t$	0.92	1.50	1.22	0.63	0.60	1.41	1.11	0.47	1.11	0.1192
$SC_{mix,i}^t$	1.04	0.99	1.06	1.04	1.03	1.00	1.02	1.14	0.99	0.0020
$SC_{enf,i}^t$	1.20	0.80	0.89	1.15	0.90	0.96	0.74	1.18	1.05	0.0249
$SC_{tot,i}^t$	1.25	1.26	1.46	0.77	0.61	1.48	0.93	0.81	1.09	0.0868
Panel D: Year 2005										
$SC_{str,i}^t$	1.08	1.03	1.23	0.90	1.10	1.12	1.10	1.27	0.94	0.0127
$SC_{int,i}^t$	0.90	1.55	1.28	0.54	0.64	1.28	1.10	0.54	1.09	0.1160
$SC_{mix,i}^t$	1.03	0.99	1.05	1.11	1.01	1.01	1.03	1.11	1.00	0.0019
$SC_{enf,i}^t$	1.23	0.79	0.86	1.22	0.93	0.95	0.78	1.01	1.04	0.0244
$SC_{tot,i}^t$	1.24	1.23	1.42	0.65	0.65	1.38	0.98	0.77	1.07	0.0795
Panel E: Year 2010										
$SC_{str,i}^t$	1.08	0.98	1.16	0.85	1.10	1.12	1.07	1.21	0.94	0.0116
$SC_{int,i}^t$	0.89	1.54	1.47	0.56	0.63	1.22	1.14	0.60	1.10	0.1208
$SC_{mix,i}^t$	1.03	0.99	1.02	1.08	1.01	1.04	1.02	1.06	0.99	0.0007
$SC_{enf,i}^t$	1.22	0.79	0.95	1.21	0.93	1.01	0.73	1.01	1.03	0.0246
$SC_{tot,i}^t$	1.21	1.17	1.66	0.62	0.65	1.43	0.91	0.79	1.06	0.1100

4.4.1.2 Results within Developing Countries

Table 4.3 shows the spatial results of the difference in energy intensity across eight developing countries in the APEC region in 1990, 1995, 2000, 2005, and 2010. Variance-8 shows the variance of each effect among eight countries, while variance-7 provides the variance among seven countries excluding China. China is the country with the highest energy intensity compared to average level of eight developing countries in the APEC region. Mexico, Peru, and Philippines are three countries with lower energy intensity compared to

the average level of eight developing countries. Intensity effect makes a key contribution to the diversity among different countries. The second last column suggests a convergent tendency within eight developing countries over years. The variance-8 of total effect becomes smaller over years indicating that the gap of energy intensity among eight developing countries is narrowed down from 1990 to 2010. China shows a significant convergent trend to the radical value over years meaning that the energy intensity in China tends to be close to the average level from 1990 to 2010. If China is excluded from developing countries, variance-7 does not show a convergent trend. It implies that except China, the energy intensity in seven developing countries becomes diverse over years.

Table 4.3 Spatial Decomposition Results of Energy Intensity within Eight Developing Countries in the APEC Region

	PRC	IDN	MYS	MEX	PER	PHL	THA	VNM	variance-8	variance-7
Panel A: Year 1990										
$SE_{str,i}^t$	0.94	1.06	1.10	1.00	0.99	0.95	0.94	0.80	0.0069	0.0078
$SE_{int,i}^t$	2.15	0.63	0.48	0.30	0.31	0.48	0.65	0.74	0.3157	0.0244
$SE_{tot,i}^t$	2.03	0.66	0.53	0.30	0.30	0.46	0.61	0.59	0.2736	0.0183
Panel B: Year 1995										
$SE_{str,i}^t$	1.04	1.04	1.10	0.96	0.94	0.90	0.93	0.83	0.0067	0.0069
$SE_{int,i}^t$	1.62	0.68	0.50	0.30	0.32	0.64	0.76	0.86	0.1519	0.0390
$SE_{tot,i}^t$	1.67	0.71	0.55	0.29	0.30	0.58	0.70	0.71	0.1644	0.0294
Panel C: Year 2000										
$SE_{str,i}^t$	1.02	1.02	1.07	0.99	0.91	0.89	0.95	0.85	0.0051	0.0052
$SE_{int,i}^t$	1.41	1.04	0.68	0.32	0.41	0.71	0.85	1.04	0.1110	0.0680
$SE_{tot,i}^t$	1.44	1.06	0.73	0.32	0.38	0.63	0.81	0.88	0.1162	0.0611
Panel D: Year 2005										
$SE_{str,i}^t$	1.03	1.03	1.04	0.99	0.95	0.93	0.96	0.87	0.0031	0.0030
$SE_{int,i}^t$	1.32	0.84	0.68	0.30	0.35	0.51	0.76	1.19	0.1190	0.0817
$SE_{tot,i}^t$	1.36	0.87	0.70	0.29	0.33	0.47	0.73	1.04	0.1159	0.0661
Panel E: Year 2010										
$SE_{str,i}^t$	1.02	1.10	0.99	1.00	1.01	0.90	1.00	0.91	0.0035	0.0038
$SE_{int,i}^t$	1.19	0.93	0.69	0.33	0.38	0.51	0.75	1.52	0.1483	0.1435
$SE_{tot,i}^t$	1.21	1.02	0.68	0.33	0.38	0.46	0.74	1.38	0.1353	0.1232

Table 4.4 presents the spatial results of the difference in carbon intensity between a specific developing country and the average level of eight developing countries in the APEC in 1990,

1995, 2000, 2005, and 2010. Variance-8 shows the variance of each effect among eight countries, while variance-7 provides the variance among seven countries excluding China. China has the highest carbon intensity over 20 years, which is much higher than other developing countries. Mexico and Peru are two countries with the lowest carbon intensity. The leading effect is intensity effect. All the other three effects, including structure effect, mix effect, and emission-factor effect, have a little contribution to the overall effect of carbon intensity. The variance-8 of total effect shows that the gap of carbon intensity among eight developing countries is narrowed down over 20 years due to the converge of intensity effect. However, if China is excluded from the group, the change of carbon intensity among the rest of seven countries shows a divergent trend over 20 years.

Table 4.3 and Table 4.4 find that the variance-8 of total effect of energy intensity is less than that of total effect of carbon intensity indicating that the difference in carbon intensity among eight developing countries is larger than the difference in energy intensity. It contrasts to the case in developed countries indicating that the difference in fuel mix and emission-factor effect contributes much to the difference in carbon intensity in eight developing countries. However, the variance-7 of total effect of energy intensity is larger than that of total effect of carbon intensity meaning that except China, the difference in other seven developing countries has a similar trend of the difference in energy intensity and in carbon intensity in developed countries. It indicates that China uses more carbon-intensive fuels and emits more carbon dioxides in the electricity generation compared to other seven developing countries.

Table 4.4 Spatial Decomposition Results of Carbon Intensity within Eight Developing Countries in the APEC Region

	PRC	IDN	MYS	MEX	PER	PHL	THA	VNM	variance-8	variance-7
Panel A: Year 1990										
$SC_{str,i}^t$	0.94	1.07	1.11	1.00	0.99	0.96	0.95	0.80	0.0077	0.0086
$SC_{int,i}^t$	2.22	0.61	0.45	0.29	0.30	0.46	0.55	0.69	0.3476	0.0197
$SC_{mix,i}^t$	1.01	0.89	0.97	0.95	0.97	1.03	1.06	1.01	0.0025	0.0028

$SC_{enf,i}^t$	1.04	0.94	0.92	0.85	0.70	0.80	0.90	0.89	0.0087	0.0059
$SC_{tot,i}^t$	2.18	0.54	0.44	0.23	0.20	0.36	0.50	0.49	0.3628	0.0160
Panel B: Year 1995										
$SC_{str,i}^t$	1.04	1.05	1.10	0.95	0.93	0.91	0.94	0.83	0.0072	0.0073
$SC_{int,i}^t$	1.66	0.66	0.48	0.28	0.32	0.60	0.66	0.80	0.1645	0.0319
$SC_{mix,i}^t$	1.01	0.87	0.98	1.00	0.96	1.00	1.06	1.00	0.0024	0.0027
$SC_{enf,i}^t$	1.04	0.91	0.85	0.83	0.71	0.82	0.88	0.80	0.0079	0.0035
$SC_{tot,i}^t$	1.80	0.55	0.45	0.22	0.20	0.45	0.58	0.54	0.2257	0.0206
Panel C: Year 2000										
$SC_{str,i}^t$	1.03	1.03	1.07	0.97	0.90	0.88	0.93	0.86	0.0054	0.0053
$SC_{int,i}^t$	1.44	1.01	0.66	0.30	0.41	0.66	0.76	0.97	0.1152	0.0592
$SC_{mix,i}^t$	1.01	0.86	0.99	1.03	0.99	1.03	1.02	1.00	0.0026	0.0029
$SC_{enf,i}^t$	1.04	0.92	0.83	0.82	0.66	0.83	0.87	0.82	0.0101	0.0053
$SC_{tot,i}^t$	1.57	0.82	0.58	0.25	0.24	0.50	0.63	0.68	0.1536	0.0402
Panel D: Year 2005										
$SC_{str,i}^t$	1.04	1.03	1.04	0.97	0.94	0.90	0.94	0.89	0.0034	0.0029
$SC_{int,i}^t$	1.34	0.82	0.66	0.28	0.34	0.48	0.68	1.09	0.1177	0.0694
$SC_{mix,i}^t$	1.01	0.85	0.93	1.02	1.01	1.06	1.01	1.02	0.0039	0.0043
$SC_{enf,i}^t$	1.03	0.94	0.90	0.81	0.68	0.82	0.88	0.81	0.0095	0.0061
$SC_{tot,i}^t$	1.45	0.67	0.58	0.22	0.22	0.38	0.56	0.80	0.1388	0.0433
Panel E: Year 2010										
$SC_{str,i}^t$	1.04	1.06	0.97	0.97	0.98	0.88	0.97	0.91	0.0032	0.0029
$SC_{int,i}^t$	1.20	0.93	0.66	0.31	0.36	0.48	0.66	1.42	0.1398	0.1272
$SC_{mix,i}^t$	1.01	0.84	1.00	1.00	1.03	1.06	1.00	1.05	0.0041	0.0047
$SC_{enf,i}^t$	1.02	0.96	0.98	0.80	0.71	0.83	0.89	0.80	0.0101	0.0080
$SC_{tot,i}^t$	1.28	0.79	0.63	0.24	0.26	0.37	0.57	1.09	0.1280	0.0813

4.4.1.3 Results between Developed Countries and Developing Countries

This sub-section first presents the comparison of energy intensity between Table 4.1 and Table 4.3. Except 1990, the variance of total effect in energy intensity among nine developed countries is always larger than that among eight developing countries meaning that the gap of energy intensity across nine developed countries is larger than that of nine developing countries in 1995, 2000, 2005, and 2010. The change of energy intensity does not show a clear trend in both developed countries and developing countries over years.

Second, this sub-section also presents the comparison of carbon intensity between Table 4.2 and Table 4.4. The variance of total effect in carbon intensity among nine developed countries is always less than the variance of total effect in carbon intensity among eight

developing countries in the APEC region in 1990, 1995, 2000, 2005, and 2010. It means that the discrepancy of carbon intensity within eight developing countries is larger than that of nine developed countries. The discrepancy of carbon intensity within developing countries shows a convergent trend. In details, the carbon intensity in China is highest compared to other countries and keeps declining over twenty years. The reduction of carbon intensity in China makes a key contribution to the convergent trend in developing countries. If China is excluded from eight developing countries, the discrepancy of carbon intensity within seven developing countries is less than the gap of carbon intensity within nine developed countries. It indicates that except China, the difference in carbon intensity in seven developing countries is smaller than that in nine developed countries. Also, the discrepancy over years becomes larger and larger in the seven developing countries. The difference shows a divergent trend over years in the seven developing countries.

Third, this study explores the difference in energy intensity between the average levels in developed countries and developing countries as shown in Table 4.5. The average level of energy intensity in nine developed countries is lower than that in eight developing countries showing that developed countries have relatively low energy intensity. Intensity effect is the key factor leading to the difference in energy intensity between the average levels of nine developed countries and eight developing countries. The total effect keeps declining in both developed countries and developing countries. It indicates that the share of developing countries in the overall economy in the APEC region becomes larger over years. The variance of total effect also goes down over years meaning that the gap of energy intensity between developed countries and developing countries is narrowed down over years.

**Table 4.5 Spatial Decomposition Results of Energy Intensity
between the Average Levels of Nine Developed Countries and Eight Developing Countries in the APEC**

Region

	Average Level of 9 Developed Countries	Average Level of 8 Developing Countries	variance
Panel A: Year 1990			
$SE_{str,i}^t$	0.98	1.22	0.0142
$SE_{int,i}^t$	0.81	2.41	0.6357
$SE_{tot,i}^t$	0.80	2.93	1.1405
Panel B: Year 1995			
$SE_{str,i}^t$	0.97	1.25	0.0191
$SE_{int,i}^t$	0.78	2.24	0.5307
$SE_{tot,i}^t$	0.76	2.80	1.0378
Panel C: Year 2000			
$SE_{str,i}^t$	0.97	1.26	0.0211
$SE_{int,i}^t$	0.80	1.98	0.3517
$SE_{tot,i}^t$	0.77	2.50	0.7441
Panel D: Year 2005			
$SE_{str,i}^t$	0.96	1.29	0.0279
$SE_{int,i}^t$	0.71	2.07	0.4646
$SE_{tot,i}^t$	0.68	2.68	0.9996
Panel E: Year 2010			
$SE_{str,i}^t$	0.95	1.27	0.0257
$SE_{int,i}^t$	0.67	1.86	0.3590
$SE_{tot,i}^t$	0.63	2.37	0.7527

Fourth, this study also provides the analysis for the difference in carbon intensity between average levels in developed countries and developing countries shown in Table 4.6. The average level of carbon intensity in developing countries is much higher than that in developed countries. The key reason is the difference in energy intensity followed by the difference in emission-factor. The variance of the effects indicators in Table 4.6 is much larger than the variance within developed countries and the variance within developing countries shown in Table 4.2 and Table 4.4. It indicates that the difference in carbon intensity between developed and developing countries in the APEC region is much more significant than that within nine developed countries and that within eight developing countries. The

trend of the difference in carbon intensity is convergent in general over twenty years. It means that the gap of carbon intensity between developed countries and developing countries is narrowed down over years mainly due to the intensity effect and emission-factor effect. Table 4.5 and Table 4.6 show that the gap of carbon intensity is larger than the gap of energy intensity between the average levels of nine developed countries and eight developing countries in the APEC region.

Table 4.6 Spatial Decomposition Results of Carbon Intensity
between the Average Levels of Nine Developed Countries and Eight Developing Countries in the APEC

Region			
	Average Level of 9 Developed Countries	Average Level of 8 Developing Countries	Variance
Panel A: Year 1990			
$SC_{str,i}^t$	0.98	1.25	0.0180
$SC_{int,i}^t$	0.80	2.51	0.7320
$SC_{mix,i}^t$	1.00	0.96	0.0003
$SC_{emf,i}^t$	0.96	1.12	0.0064
$SC_{tot,i}^t$	0.75	3.38	1.7356
Panel B: Year 1995			
$SC_{str,i}^t$	0.97	1.29	0.0259
$SC_{int,i}^t$	0.76	2.31	0.5993
$SC_{mix,i}^t$	1.00	0.96	0.0005
$SC_{emf,i}^t$	0.94	1.13	0.0089
$SC_{tot,i}^t$	0.70	3.24	1.6176
Panel C: Year 2000			
$SC_{str,i}^t$	0.97	1.30	0.0284
$SC_{int,i}^t$	0.78	2.03	0.3888
$SC_{mix,i}^t$	1.01	0.96	0.0005
$SC_{emf,i}^t$	0.94	1.13	0.0093
$SC_{tot,i}^t$	0.71	2.87	1.1664
Panel D: Year 2005			
$SC_{str,i}^t$	0.95	1.35	0.0392
$SC_{int,i}^t$	0.69	2.11	0.5067
$SC_{mix,i}^t$	1.01	0.97	0.0003
$SC_{emf,i}^t$	0.92	1.10	0.0081
$SC_{tot,i}^t$	0.61	3.05	1.4911
Panel E: 2010			
$SC_{str,i}^t$	0.94	1.33	0.0381
$SC_{int,i}^t$	0.65	1.88	0.3792
$SC_{mix,i}^t$	0.99	0.99	0.0000

$SC_{enf,i}^t$	0.91	1.08	0.0074
$SC_{tot,i}^t$	0.55	2.68	1.1320

4.4.2 Three Regional Cooperation

4.4.2.1 Background of Three Regional Cooperation

This subsection presents a general background of three economic cooperation in the APEC region including the North American Free Trade Agreement (NAFTA), the Association of Southeast Asian Nations (ASEAN), and the ASEAN Plus Three (APT) cooperation.

The NAFTA was signed by Canada, Mexico, and the United States in 1990 and implemented into force in 1994. The aim of the NAFTA is to promote the trade liberation among NAFTA partners. The agreement removes the barriers of trade and investment by eliminating most tariffs crossing borders within North America and by committing to treat each other's investors and domestic investors equally. Together with the openness to trade and investment among members, the NAFTA also establishes further cooperation regarding environmental issues and labor matters supported by the North American Agreement on Environmental Cooperation (NAAEC) and the North American Agreement on Labor Cooperation (NAALC). Since the NAFTA came into effect, the North American economy has been more than double in size. In 2010, the merchandise trade among the NAFTA members was more than three times of that in 1993. Mexico becomes a country with large foreign direct investments among emerging countries under the NAFTA.

The ASEAN is an economic cooperation of the Southeast Asian countries formed in 1967, which includes five original member states: Indonesia, Malaysia, Philippines, Singapore, and Thailand. Brunei, Cambodia, Myanmar, Laos, and Vietnam joined the ASEAN later. The ASEAN expanded to ten members by the 1990s. The ASEAN aims to build a community to promote collaboration among member states in the fields of economics, social culture, science, technology, and administration and to narrow down the development gap

among member countries. The ASEAN has developed the ASEAN Plan of Action for Energy Cooperation (APAEC) within the member countries since 1999. The APAEC promotes the regional energy cooperation regarding energy security, energy infrastructures, energy efficiency, and conservation, renewable energy and sustainability. Among several energy cooperation goals, the energy efficiency and conservation program targets to reduce the energy intensity in the member states and to promote good energy management into practices.

The APT is a forum that coordinates the cooperation between the ASEAN and other three East Asian countries including China, Japan, and Korea. The APT cooperation was initiated aiming at enforcing the financial stability in response to the Asian Financial Crisis in 1997. The following APT summits enhance the connectivity among the member countries and expand the cooperation areas to the social security, poverty reduction, labor and human resource, stable and equitable development of agriculture, fisheries and forestry, energy security, energy efficiency and conservation, environment and water resources. In 2004, the first APT Energy Ministers Meeting was held in Philippines aiming at regional energy cooperation. The APT Energy Ministers Meeting reviews the current situation of the oil market, natural gas, coal, and renewable energy. The meeting also acknowledges the importance of energy efficiency and conservation and works on the relevant studies, activities, and programs.

4.4.2.2 Results: The North American Free Trade Agreement Area

Table 4.7 presents the spatial results of energy intensity in the NAFTA region in 1990, 1995, 2000, 2005, and 2010. The energy intensity in Canada is much higher than that in Mexico and the United States mainly due to the intensity effect. The structure effect in Canada and Mexico is much higher than that in the United States. It indicates that the economies of Canada and Mexico focus on energy-intensive sector compared to the case in the United

States. The variance of total effect tends to be less from 1995 to 2010. The variance of intensity effect diminishes after 1995 while the variance of structure effect becomes larger after 1995. It indicates that the gap of energy intensity is narrowed down after the NAFTA was established, while each country's economy focuses on their specialization with the free international trade.

Table 4.7 Spatial Decomposition Results of Energy Intensity in the NAFTA Area

	CAN	MEX	USA	variance
Panel A: Year 1990				
$SE_{str,i}^t$	1.12	1.22	0.98	0.0098
$SE_{int,i}^t$	1.26	0.80	0.99	0.0360
$SE_{tot,i}^t$	1.40	0.97	0.97	0.0423
Panel B: Year 1995				
$SE_{str,i}^t$	1.07	1.15	0.99	0.0043
$SE_{int,i}^t$	1.40	0.82	0.98	0.0591
$SE_{tot,i}^t$	1.49	0.94	0.96	0.0644
Panel C: Year 2000				
$SE_{str,i}^t$	1.10	1.25	0.98	0.0124
$SE_{int,i}^t$	1.31	0.75	0.99	0.0528
$SE_{tot,i}^t$	1.44	0.94	0.97	0.0535
Panel D: Year 2005				
$SE_{str,i}^t$	1.06	1.25	0.98	0.0134
$SE_{int,i}^t$	1.36	0.84	0.98	0.0479
$SE_{tot,i}^t$	1.44	1.06	0.96	0.0426
Panel E: Year 2010				
$SE_{str,i}^t$	1.01	1.26	0.98	0.0152
$SE_{int,i}^t$	1.35	0.90	0.98	0.0392
$SE_{tot,i}^t$	1.36	1.13	0.96	0.0269

Table 4.8 shows spatial analysis results of the carbon intensity in the NAFTA area in 1990, 1995, 2000, 2005, and 2010. Canada has the highest carbon intensity compared to Mexico and United States. The main drivers causing the difference in carbon intensity are intensity effect and structure effect. It indicates that the difference in energy intensity and economic structure leads to the unbalanced carbon intensity across the three countries. For Mexico, the structure effect is significantly higher than the structure effects in other countries, which

means that Mexico's economy focuses on carbon-intensive sectors compared to Canada and the United States. The difference in carbon intensity among three countries shows a convergent trend from 1995 to 2010. Intensity effect and emission-factor effect contribute to the convergent trend, while structure effect has a negative impact on this trend. It means that after the NAFTA was implemented, the gap of energy intensity and electricity generation among the member countries becomes close due to the technological diffusion, while the difference in economic structure is larger and larger due to the specialization in the international trade. Table 4.7 and Table 4.8 show that the variance of total effect in energy intensity is larger than the variance of total effect in carbon intensity in corresponding years in the NAFTA area, indicating that the difference in energy intensity among the member countries is larger than the difference in carbon intensity in the member countries.

Table 4.8 Spatial Decomposition Results of Carbon Intensity in the NAFTA Area

	CAN	MEX	USA	variance
Panel A: Year 1990				
$SC_{str,i}^t$	1.12	1.24	0.98	0.0117
$SC_{int,i}^t$	1.27	0.77	0.99	0.0408
$SC_{mix,i}^t$	1.00	0.97	1.00	0.0002
$SC_{emf,i}^t$	0.79	0.99	1.03	0.0107
$SC_{tot,i}^t$	1.12	0.92	1.00	0.0074
Panel B: Year 1995				
$SC_{str,i}^t$	1.07	1.17	0.98	0.0056
$SC_{int,i}^t$	1.41	0.79	0.97	0.0660
$SC_{mix,i}^t$	1.01	0.99	1.00	0.0001
$SC_{emf,i}^t$	0.77	0.99	1.03	0.0138
$SC_{tot,i}^t$	1.17	0.91	0.99	0.0114
Panel C: Year 2000				
$SC_{str,i}^t$	1.11	1.26	0.98	0.0137
$SC_{int,i}^t$	1.33	0.73	0.99	0.0598
$SC_{mix,i}^t$	0.99	0.99	1.00	0.0000
$SC_{emf,i}^t$	0.79	0.99	1.03	0.0109
$SC_{tot,i}^t$	1.16	0.91	0.99	0.0104
Panel D: Year 2005				
$SC_{str,i}^t$	1.07	1.27	0.98	0.0149
$SC_{int,i}^t$	1.37	0.81	0.98	0.0547
$SC_{mix,i}^t$	0.99	0.99	1.00	0.0000
$SC_{emf,i}^t$	0.78	0.99	1.03	0.0115

$SC_{tot,i}^t$	1.14	1.02	0.99	0.0045
Panel E: Year 2010				
$SC_{str,i}^t$	1.01	1.27	0.98	0.0165
$SC_{int,i}^t$	1.35	0.87	0.98	0.0435
$SC_{mix,i}^t$	1.00	1.00	1.00	0.0000
$SC_{enf,i}^t$	0.79	0.98	1.03	0.0102
$SC_{tot,i}^t$	1.08	1.07	0.99	0.0018

4.4.2.3 Results: The Association of Southeast Asian Nations-6

Table 4.9 presents the spatial results of energy intensity in the ASEAN-6 countries in 1990, 1995, 2000, 2005, and 2010. Indonesia and Vietnam are two countries with the highest energy intensity while Singapore is the country with the lowest energy intensity. Similar to the analysis in the NAFTA countries, the leading factor causing the diverse pattern is the intensity effect. The variances of the total effect and intensity effect tend to be larger over years, while the variance of the structure effect becomes smaller over years. It indicates that the discrepancy of energy intensity becomes larger over years, while the economic structure shows a convergent trend. If Vietnam is excluded from the group, only five founding members of the ASEAN are considered in the analysis. Both economic structure and energy intensity get closer and closer over the twenty years in the ASEAN founding countries. It indicates that the ASEAN Economic Community (AEC) has a positive impact on the catch-up in economic pattern among the founding members and that the APAEC narrows down the gap of energy intensity among the founding members.

Table 4.9 Spatial Decomposition Results of Energy Intensity in the ASEAN-6

	IDN	MYS	PHL	SGP	THA	VNM	variance
Panel A: Year 1990							
$SE_{str,i}^t$	0.98	1.02	0.91	1.35	0.92	0.80	0.0295
$SE_{int,i}^t$	1.26	0.96	0.94	0.22	1.17	1.38	0.1403
$SE_{tot,i}^t$	1.23	0.98	0.86	0.30	1.07	1.10	0.0908
Panel B: Year 1995							
$SE_{str,i}^t$	0.98	1.05	0.88	1.33	0.91	0.81	0.0284
$SE_{int,i}^t$	1.19	0.86	1.09	0.17	1.28	1.44	0.1701
$SE_{tot,i}^t$	1.17	0.91	0.96	0.23	1.17	1.17	0.1109
Panel C: Year 2000							

$SE_{str,i}^t$	0.97	1.03	0.88	1.17	0.95	0.82	0.0125
$SE_{int,i}^t$	1.41	0.92	0.93	0.20	1.10	1.40	0.1660
$SE_{tot,i}^t$	1.36	0.94	0.82	0.23	1.05	1.14	0.1248
Panel D: Year 2005							
$SE_{str,i}^t$	1.00	1.00	0.93	1.11	0.95	0.82	0.0080
$SE_{int,i}^t$	1.27	1.03	0.74	0.22	1.13	1.86	0.2485
$SE_{tot,i}^t$	1.27	1.03	0.69	0.25	1.07	1.52	0.1674
Panel E: Year 2010							
$SE_{str,i}^t$	1.09	0.94	0.87	1.03	0.95	0.84	0.0074
$SE_{int,i}^t$	1.24	0.96	0.70	0.25	1.04	2.18	0.3456
$SE_{tot,i}^t$	1.35	0.91	0.61	0.26	0.99	1.84	0.2566

Table 4.10 presents the spatial analysis in the ASEAN-6 in 1990, 1995, 2000, 2005, and 2010.¹⁴ Singapore has the lowest carbon intensity while Indonesia and Vietnam have relatively high carbon intensity. Intensity effect is the leading factor for the difference, while structure effect, mix effect and emission-factor effect are less different across different countries. The variance of structure effect becomes smaller over the twenty years, while the variance of the intensity effect gets larger from 1990 to 2010. It means that the economic structure tends to be similar across different countries under the framework of ASEAN economic community, while the energy intensity diverges over the time span from 1990 to 2010. The mix effect and emission-factor effect do not show clear trends over the twenty years.

The comparison of Table 4.9 and Table 4.10 shows that the variance of total effect in energy intensity is larger than the variance of total effect in carbon intensity in the ASEAN-6 in corresponding years, indicating that the difference in energy intensity among the ASEAN-6 countries is larger than the difference in carbon intensity in the ASEAN-6 countries.

Table 4.10 Spatial Decomposition Results of Carbon Intensity in the ASEAN-6

¹⁴ Brunei is excluded from the analysis, because the data quality of energy consumption is not good as well as the data of national account is not available.

	IDN	MYS	PHL	SGP	THA	VNM	Variance
Panel A: Year 1990							
$SC_{str,i}^t$	0.99	1.03	0.92	1.31	0.92	0.80	0.0254
$SC_{int,i}^t$	1.27	0.97	0.94	0.26	1.14	1.39	0.1332
$SC_{mix,i}^t$	0.97	0.99	1.04	1.14	0.97	1.03	0.0037
$SC_{emf,i}^t$	1.01	1.02	0.91	1.14	1.00	0.98	0.0048
$SC_{tot,i}^t$	1.23	1.00	0.82	0.44	1.02	1.11	0.0645
Panel B: Year 1995							
$SC_{str,i}^t$	1.00	1.05	0.89	1.28	0.93	0.81	0.0227
$SC_{int,i}^t$	1.19	0.88	1.07	0.20	1.23	1.45	0.1596
$SC_{mix,i}^t$	0.95	1.01	1.03	1.19	1.04	1.04	0.0051
$SC_{emf,i}^t$	1.00	0.99	0.94	1.21	1.00	0.91	0.0095
$SC_{tot,i}^t$	1.13	0.92	0.92	0.36	1.19	1.10	0.0759
Panel C: Year 2000							
$SC_{str,i}^t$	0.98	1.03	0.89	1.19	0.94	0.82	0.0138
$SC_{int,i}^t$	1.41	0.92	0.92	0.22	1.09	1.40	0.1590
$SC_{mix,i}^t$	0.95	1.02	1.05	1.13	0.99	1.03	0.0031
$SC_{emf,i}^t$	1.02	0.98	0.96	1.10	1.00	0.94	0.0026
$SC_{tot,i}^t$	1.33	0.96	0.82	0.33	1.03	1.11	0.0969
Panel D: Year 2005							
$SC_{str,i}^t$	1.01	1.01	0.93	1.10	0.95	0.83	0.0068
$SC_{int,i}^t$	1.27	1.04	0.74	0.24	1.12	1.84	0.2382
$SC_{mix,i}^t$	0.94	0.99	1.07	1.13	0.99	1.04	0.0036
$SC_{emf,i}^t$	1.03	1.03	0.95	0.94	1.00	0.93	0.0017
$SC_{tot,i}^t$	1.25	1.07	0.70	0.29	1.05	1.49	0.1514
Panel E: Year 2010							
$SC_{str,i}^t$	1.08	0.96	0.88	1.04	0.96	0.87	0.0057
$SC_{int,i}^t$	1.25	0.97	0.70	0.27	1.02	2.14	0.3270
$SC_{mix,i}^t$	0.95	1.03	1.07	1.04	0.98	1.07	0.0020
$SC_{emf,i}^t$	1.03	1.09	0.93	0.92	0.99	0.91	0.0042
$SC_{tot,i}^t$	1.31	1.05	0.62	0.27	0.95	1.81	0.2393

4.4.2.4 Results: The ASEAN-6 Plus Three

Table 4.11 presents the spatial results of energy intensity in the ASEAN-6 plus three in 1990, 1995, 2000, 2005, and 2010. China is the country with the highest energy intensity followed by Vietnam and Indonesia. Singapore is the country with the lowest energy intensity followed by Japan. Intensity effect is the key factor causing the difference in energy intensity. The variance of the total effect becomes small over years indicating the discrepancy of energy intensity among the nine countries is narrowed down over years. China plays a key

role in the ‘narrowing-down’ trend. The variances of structure effect and intensity effect do not show clear trends over the twenty years.

Table 4.11 Spatial Decomposition Results of Energy Intensity in the ASEAN-6 Plus Three

	CHN	IDN	JPN	ROK	MYS	PHL	SGP	THA	VNM	variance
Panel A: Year 1990										
$SE_{str,i}^t$	1.03	1.09	0.98	0.89	1.05	0.95	1.17	0.96	0.83	0.0096
$SE_{int,i}^t$	4.86	1.50	0.41	1.00	1.25	1.20	0.34	1.49	1.78	1.5849
$SE_{tot,i}^t$	5.02	1.64	0.40	0.88	1.31	1.14	0.40	1.43	1.47	1.7047
Panel B: Year 1995										
$SE_{str,i}^t$	1.22	1.14	0.95	0.91	1.15	0.94	1.19	0.97	0.89	0.0157
$SE_{int,i}^t$	2.97	1.33	0.38	1.04	1.03	1.34	0.25	1.56	1.73	0.5681
$SE_{tot,i}^t$	3.61	1.52	0.36	0.94	1.19	1.25	0.30	1.52	1.53	0.8304
Panel C: Year 2000										
$SE_{str,i}^t$	1.18	1.12	0.94	0.97	1.11	0.92	1.15	1.02	0.90	0.0103
$SE_{int,i}^t$	2.31	1.79	0.40	0.89	1.24	1.30	0.29	1.50	1.86	0.4005
$SE_{tot,i}^t$	2.73	2.00	0.37	0.87	1.38	1.20	0.34	1.53	1.67	0.5222
Panel D: Year 2005										
$SE_{str,i}^t$	1.18	1.12	0.92	0.99	1.08	0.96	1.07	1.03	0.92	0.0076
$SE_{int,i}^t$	2.07	1.39	0.33	0.63	1.16	0.89	0.28	1.27	2.03	0.3812
$SE_{tot,i}^t$	2.44	1.56	0.31	0.63	1.26	0.85	0.30	1.31	1.86	0.4633
Panel E: Year 2010										
$SE_{str,i}^t$	1.13	1.16	0.92	0.99	1.02	0.92	1.01	1.04	0.94	0.0065
$SE_{int,i}^t$	1.70	1.39	0.30	0.55	1.06	0.79	0.30	1.13	2.33	0.4010
$SE_{tot,i}^t$	1.92	1.61	0.28	0.55	1.08	0.73	0.31	1.18	2.19	0.4307

Table 4.12 shows the spatial results of the carbon intensity in this sub-region. Variance-9 shows the variance of each effect among nine countries in the ASEAN-6 Plus Three, while variance-8 provides the variance among the rest of eight countries excluding China. China is the most carbon-intensive country in the sub-region followed by Vietnam and Indonesia. Japan and Singapore are the least carbon-intensive countries in this sub-region. The most significant effect leading to the diversity of carbon intensity is intensity effect. Other effects are relatively moderate. The comparison of panel A to panel E shows that the variance-9 becomes smaller over years indicating that the gap of the carbon intensity is narrowed down in the ASEAN-6 Plus Three region. It means that there is a convergent trend of carbon intensity in this region. Intensity effect contributes most to the convergent trend. If the extreme country (China) is excluded, the variance-8 shows that the heterogeneity of carbon

intensity across tends to be larger over the twenty years. It means that except China, the rest of eight countries have a divergent tendency in carbon intensity over years.

Table 4.12 Spatial Decomposition Results of Carbon Intensity in the ASEAN-6 Plus Three

Asean-6 Plus Three	CHN	IDN	JPN	ROK	MYS	PHL	SGP	THA	VNM	Variance -9	Variance -8
Panel A: Year 1990											
$SC_{str,i}^t$	1.05	1.09	0.98	0.90	1.07	0.97	1.11	0.97	0.84	0.0074	0.0080
$SC_{int,i}^t$	5.05	1.47	0.39	0.94	1.15	1.12	0.32	1.30	1.65	1.7651	0.1985
$SC_{mix,i}^t$	0.96	0.89	1.03	0.96	0.94	1.01	1.23	0.97	0.99	0.0083	0.0092
$SC_{emf,i}^t$	1.11	0.99	0.87	0.84	1.00	0.85	1.15	0.96	0.94	0.0109	0.0092
$SC_{tot,i}^t$	5.69	1.42	0.34	0.69	1.16	0.94	0.51	1.18	1.29	2.3432	0.1319
Panel B: Year 1995											
$SC_{str,i}^t$	1.25	1.15	0.94	0.93	1.17	0.96	1.12	1.00	0.91	0.0142	0.0102
$SC_{int,i}^t$	3.05	1.29	0.37	0.97	0.97	1.22	0.23	1.34	1.60	0.5934	0.2002
$SC_{mix,i}^t$	0.97	0.88	1.04	0.98	0.97	1.00	1.33	1.03	1.00	0.0137	0.0150
$SC_{emf,i}^t$	1.11	0.95	0.83	0.86	0.93	0.88	1.16	0.95	0.84	0.0123	0.0100
$SC_{tot,i}^t$	4.12	1.25	0.30	0.76	1.02	1.02	0.40	1.32	1.22	1.1339	0.1324
Panel C: Year 2000											
$SC_{str,i}^t$	1.22	1.13	0.93	0.99	1.13	0.94	1.12	1.03	0.94	0.0101	0.0072
$SC_{int,i}^t$	2.34	1.72	0.38	0.85	1.17	1.18	0.31	1.36	1.69	0.3792	0.2519
$SC_{mix,i}^t$	0.98	0.87	1.04	1.03	0.97	1.01	1.14	0.97	0.99	0.0046	0.0051
$SC_{emf,i}^t$	1.12	0.97	0.81	0.85	0.90	0.89	1.02	0.92	0.86	0.0083	0.0040
$SC_{tot,i}^t$	3.13	1.63	0.30	0.73	1.17	1.00	0.40	1.25	1.36	0.6282	0.1917
Panel D: Year 2005											
$SC_{str,i}^t$	1.22	1.13	0.90	1.00	1.10	0.96	1.05	1.04	0.96	0.0086	0.0050
$SC_{int,i}^t$	2.07	1.32	0.32	0.60	1.10	0.80	0.29	1.14	1.81	0.3409	0.2379
$SC_{mix,i}^t$	0.99	0.85	1.03	1.05	0.93	1.05	1.11	0.97	1.01	0.0052	0.0059
$SC_{emf,i}^t$	1.08	0.98	0.82	0.81	0.96	0.87	0.84	0.90	0.85	0.0070	0.0036
$SC_{tot,i}^t$	2.70	1.25	0.24	0.51	1.07	0.70	0.29	1.05	1.49	0.5104	0.1846
Panel E: Year 2010											
$SC_{str,i}^t$	1.17	1.13	0.90	1.00	1.02	0.92	1.00	1.04	0.97	0.0071	0.0047
$SC_{int,i}^t$	1.69	1.35	0.29	0.53	0.98	0.72	0.31	1.00	2.10	0.3428	0.3181
$SC_{mix,i}^t$	1.00	0.84	1.02	1.07	0.99	1.05	0.99	0.97	1.05	0.0040	0.0045
$SC_{emf,i}^t$	1.05	0.99	0.80	0.84	1.03	0.86	0.84	0.91	0.83	0.0082	0.0061
$SC_{tot,i}^t$	2.08	1.28	0.22	0.47	1.02	0.60	0.26	0.93	1.76	0.3791	0.2492

4.4.2.5 Comparison among the NAFTA, the ASEAN-6, and the ASEAN-6 Plus Three

This sub-section compares the results in sub-section 4.4.2.2, 4.4.2.3, and 4.4.2.4, and analyzes the impact of economic cooperation on the discrepancy of energy intensity and carbon intensity among member countries.

The NAFTA has been implemented since 1994, which focuses on eliminating the trade barriers in member countries. Based on classical economic theory, the free trade permits specialization among countries. The economy in each member country shifts to the specialized sectors. An increasing diversity of the economic structure drives up the discrepancy of energy intensity and carbon intensity among member countries. On the other hand, technological diffusion narrows down the gap of energy efficiency leading to a convergent trend of intensity effect and emission-factor effect among member countries. It indicates that a less diversity of intensity effect and emission-factor effect narrows down the discrepancy of energy intensity and carbon intensity among member countries.

The ASEAN was initiated by six founding members and then expanded to ten countries, which aims at social and economic cooperation and narrowing the development gap among member countries. The member countries of the ASEAN also sign the APAEC, in which one goal is to promote energy conservation. The spatial analysis for the ASEAN-6 shows that a convergent economic structure leads to a less difference in energy intensity and carbon intensity among the ASEAN-6 countries. Among six countries, only Vietnam, a less developing country in the ASEAN-6, shows a sharp increase in intensity effect over years compared to the average level of the ASEAN-6. If Vietnam is excluded from the group, other five founding members have a convergent trend in intensity effect over years indicating that the APAEC does work in the five founding members. The mix effect and emission-factor effect do not show clear trends over twenty years.

Formed in 1997, the APT initially focuses on the financial stability and then deepens and broadens the cooperation from the perspective of political-security, economy, finance, sustainability, and social culture. Compared to the NAFTA and the ASEAN, the APT has a relatively short history and a loose bonding and connection among member countries. The APT-9 area does not show a clear trend of the difference in energy intensity and carbon intensity among member countries. China had an extremely high energy intensity and carbon intensity in 1990 and then experienced a sharp reduction in energy intensity and carbon intensity over twenty years.

4.5 Conclusion

This study investigates whether there is a convergent tendency in energy intensity and carbon intensity across the APEC countries over years and which factors influence the trend using the spatial IDA method. The discrepancy in energy intensity among countries is attributed to structure effect (the difference in economic structure) and intensity effect (the difference in sectoral energy intensity). The gap in carbon intensity across countries is due to structure effect (the difference in economic structure), intensity effect (the difference in sectoral energy intensity), mix effect (the difference in energy structure), and emission-factor effect (the difference in emission-factor).

This study explores two broad questions. First, this study examines the difference in energy intensity and carbon intensity within and between nine developed countries and eight developing countries in the APEC region. Second, this study explores the role of three economic cooperation organizations within the APEC region: the NAFTA, the ASEAN-6, and the APT-9. The results show the impact of economic cooperation on the difference in energy intensity and carbon intensity among the member countries.

This study conducts three spatial analyses for the discrepancy of energy intensity and carbon intensity a) within nine developed countries, b) within eight developing countries, and c) between the average levels of nine developed countries and eight developing countries in the APEC region. Nine developed countries do not show a clear trend in energy and carbon intensity over twenty years, while eight developing countries show a convergent tendency in energy and carbon intensity over years mainly contributed by China. The leading factor of the difference in energy intensity and carbon intensity is intensity factor. The comparison of analysis a) and b) shows that the energy intensity pattern and carbon intensity pattern are more unbalanced in eight developing countries than those in nine developed countries. The fuel structure and electricity generation process are more diverse among developing countries than those in developed countries. In analysis c), there is a convergent trend in energy and carbon intensity between the average level of developed countries and developing countries. Intensity effect is the key factor. The difference in carbon intensity is more significant than the difference in energy intensity between developed countries and developing countries. The comparison of analysis a), b), and c) shows that the discrepancy in energy and carbon intensity in 'between analysis' is much more significant than the discrepancy in two 'within analyses'.

This study also conducts three spatial analyses for the discrepancy in energy intensity and carbon intensity among member countries in three economic cooperation organizations: a) the NAFTA countries, b) the ASEAN-6 countries and c) the ASEAN-6 plus three countries. In analysis a), there is a convergent trend in energy and carbon intensity among member countries of the NAFTA. The free trade agreement promotes the specialization in the NAFTA countries leading to an increase in the economic structure gap among three countries. In contrast, the technological diffusion reduces the gap of energy efficiency among three countries narrowing down the difference in energy and carbon intensity. In

analysis b), there is a divergent tendency in energy and carbon intensity in the ASEAN-6 countries. Although the economic structure tends to be closer in the ASEAN-6, an increasing difference in intensity effect leads to a divergent trend in energy and carbon intensity among the ASEAN-6 countries. Among six countries, Vietnam shows a sharp increase in intensity effect over years compared to the average level of the ASEAN-6. If Vietnam is excluded from the group, other five founding members have a convergent trend in intensity effect over years indicating that the energy efficiency policy works in the ASEAN region. In analysis c), the APT area does not show a clear trend in energy intensity and carbon intensity among member countries. The possible reason is that the APT-9 has a relatively short history and a loose bonding and connection among member countries.

The comparison among different regional cooperation points out that a strong connected regional cooperation (e.g., the ASEAN) regarding economic development and energy efficiency greatly helps enhance the convergence of energy and carbon intensity. The free trade agreements also play roles to narrow down the gap of energy and carbon intensity among member countries over years mainly through the channel of technological diffusion. But the free trade agreements promote the specialization of economic structure in member countries, which leads to a divergent trend of energy and carbon intensity.

5 Summary

This thesis consists of three self-contained essays on the topic of “resource use, technology, and climate”. This section summarizes the thesis and discusses the future research related to the thesis.

Chapter 2 investigates the impacts of the emissions abatement policies and energy R&D investments on the resource use, climate change, economic gains, and abatement costs in the framework of two-sector multiple-resource hybrid model over the time span from 2005 to 2155. There are four key findings in this study. First, this study finds two energy R&D investments affect resource substitution and economic welfare through different channels. The replacement of backstop for fossil fuels is completed earlier of ten years in the model with RB than that in the model without RB. Second, the study presents the resource use sequences in the capital goods sector and the consumption goods sector. The sequences of resource use are a) oil products, followed by coal products, followed by backstop energy in the capital goods sector, and b) natural gas, followed by oil products, followed by coal products and followed by backstop energy in the consumption goods sector. Third, this study explores the impact of energy-related carbon emissions on the change of atmospheric temperature. The highest atmospheric temperature is constrained at 2.53°C in 2115 in the optimal policy scenario, which is lower of 0.25°C than the BAU scenario. Fourth, this study analyzes the economic gains and the abatement costs across different policies. The implication is that the more restrictive the policy is, the more severe economic damage is caused in the short run, but the more economic welfare is gained in the long run. The abatement costs are much higher in the 2°C scenario than those in the optimal policy scenario.

There are three main limitations in chapter 2. First, this study simplifies the overall economy into two sectors: consumption goods sector and capital goods sector. The simplification

leads to omitting some specific features in other sectors in reality. If the data of energy costs can be found in sectors at the high-resolution level, the resource use pattern can be more close to the realistic case. Second, this study assumes that the primary energy is converted to final energy service in one step. This assumption simplifies the process of energy transformation. In reality, the primary energy is converted to the secondary energy and then converted to the final energy service. If the specific data of the energy transformation are available, this study can look into the details of the resource use pattern through a two-step energy transformation technology. Third, another problem caused by the simplification is that this model does not explicitly include electricity sector. The detailed features of energy transformation in the electricity sector are not captured explicitly in this model. Future study can fill the blank by incorporating the technological features of electricity sectors into the model.

Chapter 3 aims to investigate the drivers and trends of energy consumption and carbon emissions in 17 APEC countries from 1990 to 2010 employing the temporal IDA method. The 17 APEC countries are grouped into developed countries and developing countries. First, the intensity effect is a key factor that has a significantly negative impact on energy consumption and carbon emissions in developed countries. Other effects, such as structure effect, mix effect, and emission-factor effect, are relatively mild compared to the intensity effect in developed countries. Second, the activity effect is a key driver leading to a rapid increase in energy consumption and carbon emissions in developing countries. The activity effect is higher in developing countries than that in developed countries, while the intensity effect is relatively insignificant in developing countries compared to the case in developed countries. Third, this study also examines the impact of extreme macroeconomic events on the drivers. The economic shocks affect the energy consumption and carbon emissions

through the activity effect, but they hardly change energy structure and energy efficiency in the short run.

Chapter 4 investigates whether there is a convergent tendency in energy intensity and carbon intensity across the APEC countries over years and which factors influence the trend using the spatial IDA method. First, this study examines the discrepancy in energy intensity and carbon intensity within and between nine developed countries and eight developing countries in the APEC region. The difference in energy intensity and carbon intensity between developed countries and developing countries is much more significant than that within nine developed countries and that within eight developing countries. The key factor is intensity effect. Over twenty years, nine developed countries do not show a clear trend in energy and carbon intensity, while eight developing countries show a convergent tendency in energy and carbon intensity over years mainly contributed by China. Second, this study explores the role of three economic cooperation organizations within the APEC region: the NAFTA, the ASEAN-6, and the APT-9. The member countries in the NAFTA show a convergent trend in energy and carbon intensity mainly due to a convergent trend in intensity effect. In contrast, the gap of economic structure among three countries becomes large as the free trade agreement promotes the specialization in the NAFTA countries. The ASEAN-6 countries have a divergent tendency in energy and carbon intensity. Although the economic structure tends to be closer in the ASEAN-6, an increasing difference of intensity effect leads to a divergent trend in energy and carbon intensity among the ASEAN-6 countries. The APT-9 does not show a clear trend of the difference in energy intensity and carbon intensity among member countries. The possible reason is that the APT-9 has a relatively short history and a loose bonding and connection among member countries. A policy implication is that a strong connected regional cooperation (e.g., the ASEAN)

regarding economic development and energy efficiency can help enhance the convergence of energy and carbon intensity.

Chapter 3 and Chapter 4 mainly have two limitations. The first limitation is about the data quality. The energy data in this analysis are mainly taken from the IEA database and the APEC EWG database. They are the best and most reliable database that currently found. If the energy data released by the local government are available, the analysis based on the local data can be more accurate. Second, this study divides the overall economy into four sectors, which is at a low-resolution level. As Ma and Stern (2008) suggests, the decomposition analysis at different level leads to different decomposition results. The analysis at a low-resolution level underestimates the structure effect and overestimates the intensity effect compared to the analysis at a high-resolution level. Extending the decomposition analysis to more countries cannot avoid sacrificing the resolution level in each country due to the unavailability of detailed energy data. In the future, if the energy database with high resolution is available, the decomposition analysis can be conducted more accurately.

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