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Ph. D. Dissertation in Engineering

Separability and Substitutability between Energy and Capital: Evidences from KLEM Analyses of 10 OECD Countries

August 2012

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Abstract

The KLEM model is one of the major recognized ways to analyze industrial energy demand utilizing an econometric method. Since the study of Berndt and Wood (1975), which established the KLEM model, it has been globally applied in energy economics. Using the model, both interfactor substitutability and interfuel substitutability are examined. Applying the KLEM model, this thesis conducts in-depth analyses of substitutability between energy and capital.

There are two main issues with regard to substitutability between energy and capital. The first issue is the assumption of separability that generally prevails in many applied studies of the KLEM model.

Separability allows us to aggregate dozens of input factors all into four: capital (K), labor (L), energy (E), and material (M). The assumption of separability restricts the possibility of sophisticated analysis of substitutability between energy and capital in the industrial sector. The definition of "separability between energy and capital" is a condition where substitution among various capital assets is irrelevant to substitution among various energy sources. However, in the industrial sector, the type of capital facility invested in tends in practice to determine the choice of energy source. That is, the assumption of separability ignores changes in energy mix induced by the investment of a particular kind of capital asset.

The second issue is whether energy and capital are substitutable for one another. Since the "energy–capital hypothesis" was demonstrated by Griffin and Gregory (1976), many researchers have investigated this issue. This argument is important because if capital can substitute for energy, the adoption of energy-saving technologies through capital investment will be available. Despite many previous discussions, a consensus has not been achieved on this issue. Meanwhile, the adoption of energy-saving technologies through capital investment can be achieved, meaning that substitution of capital for energy dominates substitution of energy for capital. Many

literatures on this issue overlook the question of direction of substitution, focusing instead on the general issue of substitutability. However, a few studies (Thompson and Taylor, 1995; Welsch and Ochsen, 2005; Feng and Serletis, 2008) have shown that substitutability between energy and capital is actually asymmetric.

In this context, this thesis studies separability and substitutability between energy and capital. To achieve general discussions, the manufacturing sectors of the following 10 OECD (Organization for Economic Cooperation and Development) countries after 1980 are separately analyzed: Australia, Austria, Denmark, Finland, Italy, Japan, Republic of Korea (Korea), Netherlands, the United Kingdom (UK), and the United States (US).

This thesis investigates three research topics. The first is whether the assumption of separability between energy and capital is theoretically appropriate. After defining the sub-factors of energy and capital, cases of separability with corresponding separability patterns to the cases are specified. The test results for the three separability cases and the sixteen corresponding separability patterns show that the assumption of separability is not theoretically permissible. These results indicate that it is better to divide energy and capital into sub-inputs.

Second, the differences in demand for the four types of energy sources, *i.e.*, coal, oil, gas, and electricity induced by the investment of various capital assets are investigated. Capital assets are classified into six types: ICT assets, transport equipment, other machinery, other assets, non-residential structures, and residential structures. The energy sub-model (Fuss, 1977), a part of the KLEM model, is extended by the addition of a variable regarding capital investment; then, it is applied to this investigation.

The empirical results show that ICT assets, other machinery, and other assets increase electricity demand, while transport equipment, non-residential equipment, and residential equipment decrease it. Thus, based on their effect on electricity demand, capital assets can be classified into two groups; capital that increases demand (EK) and capital that does not (NK). Besides, the extended energy sub-model regarding the investment of EK and NK tends to yield better performance in econometric and economic regularities than the energy sub-model. An international comparison also shows that the higher energy independence, the lower interfuel substitutability.

Third, in the case where capital and energy are divided into sub-inputs based on their interaction, features of substitutability between energy and capital are analyzed by applying the KLEM model. In

particular, the source of the disagreement on the substitutability between energy and capital (i.e., the assumed input factors) and the direction of substitutability between them are contemplated. Five input factors—EK, NK, electricity, fuel, and *Other* (the aggregate of labor and material)—are assumed.

Estimates of the Morishima elasticity of substitution (Blackorby and Russell, 1989; Morishima, 1967) demonstrate that substitution of energy for capital has dominated substitution of capital for energy. In particular, both EK and NJ tend to complement fuel. This asymmetry corresponds to the energy demand behavior engaged in Hartman (1979). Also, the asymmetry supports the contention of previous studies that energy pricing has failed to induce the adoption of energy-saving technologies (de Groot et al., 2001; OTA, 1993; Kim, 2010; Velthuijsen, 1993). Finally, this thesis finds an uncertain tendency in the features of interfactor substitutability by country type.

The contribution of this thesis can be summarized in five points. The first is its theoretical contribution to application of the KLEM model. This thesis is the first study that conducts an in-depth investigation of separability between energy and capital, using the KLEM model. The second point is that the thesis provides a new look at the classification of capital assets, showing that capital assets

invested in the manufacturing sector can be classified into two types by their effect on electricity demand. The third point relates to the generalization of substitutability between energy and capital in the ten major countries. Substitutability between energy and capital has been a major topic in energy economics since the 1970s. This study contributes to the development of a generalized discussion on this topic. The fourth point is the implications of the study for industrial energy policy. Analysis of asymmetric substitutability shows that energy pricing does not effectively reduce industrial energy demand. The fifth point refers to the study's empirical contribution to the theory of economic growth. This thesis compares interfactor and interfuel substitutability in the manufacturing sectors of the ten OECD countries.

Keywords: KLEM model, Separability, Interfactor substitutability, Interfuel substitutability, Substitutability between energy and capital

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INTRODUCTION AND RESEARCH FRAMEWORK

1. Motivation

The KLEM model is one of the representative methods used to analyze industrial energy demand using an econometric method. Since the monumental study of Berndt and Wood (1975), which established the KLEM model, it has been globally applied in energy economics. Using this model, interfactor substitutability and interfuel substitutability are examined, since then. Interfactor substitutability describes how the demand for input factors, such as capital, labor, energy, and material, responds to price changes in these factors. Interfuel substitutability tells how the demand for different energy sources, such as coal, oil, gas, and electricity, responds to changes in their price. In energy economics, it has been noted that economic growth can continue even when energy demand is substituted by other input factors (Koetse et al., 2008). Substitution of low-carbon for high-carbon fuel in the industrial sector has also received substantial attention (Stern, 2009). In summary, the application of the KLEM model yields important information on how economic growth and energy price changes have affected industrial energy demand.

In many applied studies of the KLEM model, the assumption of

separability should be made. The concept of separability allows us to aggregate a bunch of inputs into a few input factors (Leontief, 1947). Aggregation of inputs is very useful, because it is hard to consider dozens of input factors in the real production process. Therefore, it is common to aggregate various input factors into capital (K), labor (L), energy (E), and material (M) within a theoretically permissible range, which is determined by separability. That is why the name of the model is the KLEM model.

The concept of separability restricts precise analysis of substitutability between energy and capital. This substitutability has been an important issue, in part because the uptake of an energy-saving technology can be represented by the substitution of capital for energy (Stern and Cleveland, 2004). Separability between capital and energy means that cost-minimizing or profit-maximizing choice in the energy mix is independent of the capital mix (Fuss, 1977). However, this condition does not correspond to actual decision making in the industrial sector, because the type of capital facility invested is more likely to determine the choice of energy source. If separability is assumed and this connection between energy and capital overlooked, substitutability between energy and capital may not be accurately assessed.

Some literature empirically analyzing the KLEM model has

reported that substitutability between energy and capital is different both by type of capital and by type of energy. Field and Grebenstein (1980) and Garofalo and Malhotra (1988) showed that it is different by capital type, whereas Hesse and Tarkka (1986), Ilmakunnas and Törmä (1989), Caloghirou et al. (1997), and Kim and Heo (2010) proved that it is different by energy type. Those results are circumstantial evidence of the limit of assumable separability between energy and capital.

Another issue with regard to the empirical analysis is whether energy and capital are substitutable for one another. If so, capital investment may reduce energy demand. If not, capital investment will not guarantee a reduction of energy demand. This issue was first covered in Berndt and Wood (1975), who asserted that these two input factors complement each other in US manufacturing. In turn, Griffin and Gregory (1976) refuted Berndt and Wood (1975), suggesting instead the "energy–capital hypothesis," the essential point of which is that there exists substitutability between energy and capital. This hypothesis began with the idea that increases in energy efficiency are available through increased investment, either by retrofitting existing plants and equipment or through new engineering designs.

Many studies have discussed the "energy–capital hypothesis":

Pindyck (1979), Griffin (1981), Truong (1985), Christopoulos (2000), Bentzen (2004), and Koetse et al. (2008) supported the argument of Griffin and Gregory (1976); however, Fuss (1977), Berndt and Khaled (1979), Berndt and Wood (1979), Anderson (1981), Denny et al. (1981), Prywes (1986), and Kim (2009) sided with Berndt and Wood (1975). That is, there is no consensus on substitutability between energy and capital. In the present paper, assumptions regarding the input factors constituting the source of this disagreement on substitutability are considered (Koetse et al., 2008).

In sum, a condition of separability between energy and capital has been tacitly assumed for the convenience of applied study using the KLEM model. However, this assumption does not reflect decision making in the real economy, and its limit has been found in some prior studies. Thus, separability between energy and capital should be investigated in earnest. The present work is a precursor to the future more sophisticated substitutability between energy and capital. Substitutability between energy and capital is an important issue because it is related to the adoption of energy-saving technologies through capital investment.

2. Research Purpose

This thesis contemplates separability and substitutability between energy and capital through the framework of the KLEM model. To make a general discussion possible, the manufacturing sectors of the following 10 OECD (Organization for Economic Cooperation and Development) countries after 1980 are separately analyzed: Australia, Austria, Denmark, Finland, Italy, Japan, (the Republic of) Korea, the United Kingdom (UK), and the United States (US). This thesis aims to investigate three research questions.

First, is it appropriate to assume that energy is separable from capital? The concept of separability is designed to achieve convenience in application of the KLEM model, as well as ease of interpretation. Thus, this question can be translated to one on whether the assumption of separability between energy and capital is theoretically permissible. If this assumption is not appropriate, energy and capital had better be divided into sub-inputs. Further, that situation would imply that previous discussions of substitutability between energy and capital should be reconsidered.

Second, are demand for coal, oil, gas, and electricity, respectively differentiated by the investment of the individual capital asset? If energy is not separable from capital, the investment of a certain

capital asset may influence interfuel substitutability itself. This indicates that the type of capital asset invested can change the demand of the individual energy source in a unilateral way. If the effects of capital assets on the demand of the individual energy source are revealed, it is better to consider these capital assets when analyzing interfuel substitutability. This approach also contributes to deciding how to divide energy and capital into sub-inputs in application of the KLEM model.

Third, can energy be substituted by capital? This issue has been discussed in many studies since Berndt and Wood (1975) and Griffin and Gregory (1976), but no consensus has yet been reached. Koetse et al. (2008) argue that one of the reasons for this disagreement is the difference in the types of capital assets and energy sources assumed in previous literature. Thus, when capital and energy are divided into sub-inputs to consider their interaction, it will be helpful to provide a generalized result regarding substitutability between energy and capital. This thesis also considers whether the substitution of capital for energy dominates the substitution of energy for capital.

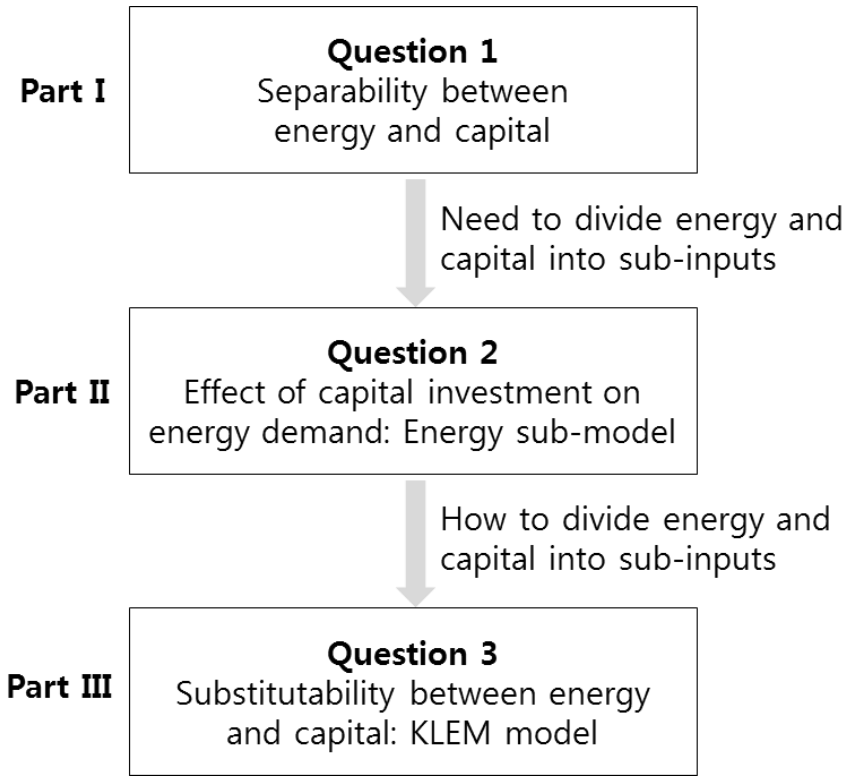
This thesis is the first study that seriously investigates separability between energy and capital, a condition that has been conventionally assumed. It can be referred to by other applied studies of the KLEM model, and is applicable to academic discussion on the classification

of capital assets. As well, this investigation allows us to measure substitutability between energy and capital in a more sophisticated manner. An international comparison is conducted to develop a consensus on these issues. Further, this thesis considers the characteristics of the structure of the production process and industrial energy demand in ten major countries. It can be referred to in the formulation of the economic and industrial energy policies of countries around the world.

3. Research Framework and Thesis Outline

This thesis consists of six chapters in total. After the introduction and research framework, in the first chapter, the second explains the KLEM model, which is the primary approach used in this thesis, and its theoretical foundation. Then, the three research questions outlined above are dealt with in the following three chapters. These three chapters are named Part I, Part II, and Part III. Figure 1 presents the research framework of this thesis.

Figure 1. Research Framework



Part I investigates whether the assumption of separability between energy and capital is appropriate. That is, this chapter deals with the first research question. Assuming that the capital aggregate consists of three capital assets and the energy aggregate four energy sources, three cases and sixteen separability patterns are derived. Then, whether separability between energy and capital is theoretically permissible can be contemplated.

Part II provides a possible answer to the second research question. Applying the energy sub-model (Fuss, 1977), the issue of whether the demand of the individual energy source is affected by the type of capital asset is analyzed. Specifically, the capital aggregate is divided into six assets to capture in detail their effects on the demand for the individual energy source. Through this procedure, how to categorize the six capital assets and four energy sources by the energy use they induce is discussed. Further, interfuel substitutability in the manufacturing sectors of the 10 OECD countries covered is examined in terms of the effects of various capital assets on demand for individual energy sources.

Part III focuses on the third research question, substitutability between energy and capital. Based on the input categorizations in Part II, interfactor substitutability is analyzed by the KLEM model

(Berndt and Wood, 1975). Then, this thesis tries to find the source of disagreement on the question of substitutability between energy and capital and to come up with a generalization about substitutability between energy and capital in the 10 countries. Moreover, asymmetric substitutability between energy and capital is considered. Thus, this thesis tries to determine whether energy-saving technologies have been adopted through capital investment.

The final chapter summarizes the main results of this thesis, and clarifies its contributions to academic study and energy policy.

4. Literature Reviews

4. 1. Interfactor Substitutability

This section introduces briefly previous literatures on interfactor substitutability by applying the KLEM model. In particular, it focused on presenting results concerning substitutability between energy and capital, which was triggered by the arguments of Berndt and Wood (1975) and Griffin and Gregory (1976).

Berndt and Wood (1975) characterized the production technology in the US manufacturing. They analyzed time series data of KLEM from 1947 to 1971, and assumed a translog production structure. They found that the energy demand is price-responsive, and energy and capital are complementary. Until their study, no emprical study had explicitly investigated substitutability between energy and nonenergy inputs.

In turn, Griffin and Gregory (1976) analyzed substitutability between energy and capital. They applied a translog approximation of a production technology and used pooled international data for manufacturing that include Belgium, Denmark, France, West Germany, Italy, Netherlands, Norway, the UK, and the US. They found that energy and capital are substitutable in these countries. The

major contribution of their study is they captured substituability in the long run by analyzing a pooled data. Thus, they raised the argument on the choice of dataset, *i.e.*, time-series data vs. pooled data.

Fuss (1977), which firstly proposed the energy sub-model, analyzed both interfuel substitutability and interfactor substitutability. He found a linkage between the energy sub-model explaining energy demand and the model explaining the demand for the aggregate inputs, and this linkage was lately named as the two-stage KLEM model. He investigated the Canadian manufacturing sector from 1961 and 1971, and in particular, he analyzed a pooled time series data that covers five regions. By a translog approximation, he found that energy and capital are complementary.

Magnus (1979) examined the substitution between factors in response to price changes. He opted for an extension of Diewert's Generalized Cobb-Douglas unit cost function and anlyzed the annual time-series for the Netherlands, 1950-1976. His estimates of elasticities of substitution told that energy and capital appeared to be close complements and the magnitudes of complementarity were considerably elastic.

Pindyck (1979) provided evidences on the role of energy in the production structure which support the contention of Griffin and

Gregory (1976). The data covers the industrial sectors of the ten countries from 1963 to 1973: Canada, France, Italy, Japan, the Netherlands, Norway, Sweden, the UK, the US, and West Germany. He analyzed the two-stage KLEM model by a translog approximation and assumed capital, labor, and energy as input factors. The empirical results revealed that energy and capital are substitutes in the long run.

Field and Grebenstein (1980) tried to disclose a cause of the arguments on the role of energy. They divided capital into physical capital and working capital, and assumed the two capitals, labor, and energy as input factors. They constructed a pooled data consisting of ten industries within the US manufacturing sector. They found that physical capital and energy are complementary, except the fabricated metals and instruments industry. However, working capital and energy are substitutable in all the industries. So, the main contribution of their study refers to that substitutability between energy and capital is different by capital type.

Harper and Field (1983) reported elasticities of substitution estimated from region-specific models containing inputs of capital, labor, energy and material. Namely, their purpose was to search for interregional differences in characteristics of the production functions in the US manufacturing. Utilizing a translog approximation, they found that substitutability between energy and capital was different

by region.

Turnovsk et al. (1982) investigated interfactor substitutability in the Australian manufacturing sector with emphasis on energy inputs. Analyzing time-series data, they supported the view that the different substitutability between energy and capital cannot be reconciled simply on the basis of pooled or time-series data. Incorporating capital, labor, energy, and material as input factors, they found that energy and capital are elastically substitutable.

Garofalo and Malhotra (1984) compared substitutability among capital, labor, and energy in 1963~1966 to that in 1974~1977. They composed internationally pooled time series data, and the manufacturing sectors of nineteen regions in the US were included in the dataset. Complementarity and Substitutability were mixed in the regions. Noticeably, for the periods 1974~1977 capital and energy were mildly complementary in the whole nation. The result for the 1963~1966 period were somewhat different, and they were mildly substitutable in this period.

Truong (1985) empirically estimated the two-stage KLEM model. The object of analysis is time series data from 1968~1969 to 1980~1981 of the manufacturing sector in the New South Wales region, Australia. As input factors, capital, labor, energy, and material were defined. Especially, he approximated the production structure

by utilizing the Rotterdam model. The result indicated that energy and capital substitutes each other.

Hesse and Tarkka (1986) analyzed the KLEM model for the manufacturing sectors in the west European countries. Two sample periods are separately estimated, *i.e.* from 1960 to 1972 (period 1), and from 1973 to 1980 (period 2). Cross section time series data is analyzed, and a translog model is used for the approximation of the production structure. Input factors were assumed as capital, labor, electricity and fuel. In the period 1, substitution and complementarity are mixed between electricity and capital. In the period 2, substitution between electricity and capital is confirmed in the every country analyzed. Meanwhile, capital and fuel substitutes each other in both the period 1 and the period 2. Their results indicate some quite significant changes in the elasticities over the two periods.

Iqbal (1986) estimated interfactor substitution in the following five manufacturing sectors using the KLEM model; the paper, machinery, and metal product manufacturing; the textiles, food and basic metals manufacturing; the rubber, chemical and electrical machinery manufacturing; the transport, tobacco, and no-metallic products manufacturing; and the leather, footwear, printing and miscellaneous industries. The sample period covered from 1959 to 1970, and cross-section time series were analyzed. Given the

approximation by a translog function, the two-stage KLEM model which assumes capital, labor, and energy, was estimated. Estimates of Elasticities showed that energy and capital are substitutes. However, values of elasticities of substitution are low, implying that demand die not respond much to changes in the relative prices of inputs.

Saicheua (1987) analyzed cross-section time series data of the manufacturing sector in Thailand from 1974 to 1977. The production structure is approximated by the translog cost function. Three factors, *i.e.* capital, labor, and energy, are assumed as inputs. In all the five sub-industries of the manufacturing sector, capital and energy substitutes each other. The results indicate that the labor-intensive and comparative advantage-based industries showed greater responsiveness to energy price changes relative to the capital-intensive and protected industries in the sense that the former two can substitute capital and labor for energy whereas the latter two can substitute only capital.

Chung (1987) investigated substitutability among capital, labor, energy, and material in the US manufacturing sector. Using the same dataset of Berndt and Wood (1975), he proposed an alternative way to compute the Allen elasticity of substitution, i.e. the Durbin procedure, and contended this method substantially simplifies econometric problems. Using this new method, they found substitutability

between energy and capital, which is contrary to Berndt and Wood (1975). However, his method has not been generally applied in empirical studies of the KLEM model.

Kim and Labys (1988) analyzed the production structures of nine industries in the manufacturing sector, the total manufacturing sector, the agricultural sector, the mining sector, the construction sector, and the total industry which includes these sectors. They composed pooled time series dataset covering from 1960 to 1980. Substitutability and complementarity were mixed at the sub-industry level. However, in the total manufacturing and the total industry, energy and capital appeared to be substitutable.

Morrison (1988) evaluated the patterns of the factor demands of Japanese and US manufacturing. She suggested a short-run extension of the Generalized Leontief function that explicitly incorporates the effects of the quasi-fixed inputs (e.g. capital and labor) and presented short- and long-run interfactor substitutability. Capital, labor, energy, and material are assumed as input factors. Complementarity between energy and capital in both countries was found. And Substitutability of other inputs to accommodate energy price shocks appears stronger in Japan than the US.

Andrikopoulos et al. (1989) investigates the times series data from 1962 to 1982 of the manufacturing sector in the Ontario,

Canada. They estimated the two-stage KLEM model approximated by the translog model. In the paper and allied, non-metallic, primary metals, chemical, and transport equipment industries, energy and capital substitutes each other. However, they complement each other in the food and beverage, and other manufacturing industries.

Ilmakunnas and Törmä (1989) analyzes the Finnish manufacturing sector by the generalized Leontief KLEM model. Input factors are assumed as capital, labor, electricity, fuel, and material. They compare interfuel substitutions in the two periods, *i.e.*, from 1960 to 1973 and from 1974 to 1981. They find a shift from capital-energy complementarity in the period 1960-1973 to capital-energy substitutability in the period 1974-1981.

Sterner (1989) analyzes the cross-section time series data from 1966 to 1981 of the various industries belonging to the Mexican manufacturing. Five input factors are assumed as follows; capital, labor, electricity, fuel, and material. The translog model is applied to approximate the production structure. He found that substitutability between energy and capital is different by energy source. The results show that a policy of heavy subsidies to domestic energy consumption is the main reason for growing energy intensity.

McNown et al. (1991) examined substitutability among capital, labor, and energy in manufacturing sectors of the three Asian

countries: India; Pakistan; and Bangladesh. Applying a translog cost function, they observed substitutability between energy and capital in all three countries. This substitutability is inelastic in India and Pakistan while it is elastic in Bangladesh.

Yuhn (1991) undertakes an empirical investigation of the issue that the size of the elasticity of substitution between factors is relevant to economic growth, *i.e.*, the de la Grandville hypothesis. This study analyzed interfactor substitutability of the Korean manufacturing and then, compared it to interfactor substitutability of the US manufacturing. The production technology was assumed to be related with capital, labor, energy, and material. This study found a substantial substitutability between energy and capital. It also supported the de la Grandville hypothesis, demonstrating that the estimates of the elasticity of substitution in Korean manufacturing tend to be considerably higher than those of the US manufacturing.

Watanabe (1992) tried to prove this hypothesis on the basis of an examination of the trends in the substitution of production factors by technology as represented by R&D investment efforts. This paper analyzed the Japanese manufacturing sector from 1970 to 1987 and constructed a time-series dataset. Incorporating capital, labor, energy, and material in the input factors, he found substantial substitutability between energy and capital.

Jha et al. (1993) analyzes separately interfuel substitution in the four major industries (cement, electricity and gas, cotton textiles, iron and steel, and total industries) of India, from 1960~61 to 1982~83. Input factors are capital, labor, energy, and material, and the translog function approximates the production structure. On the average, energy and capital complements each other in the total industry while they substitute in the other four industries.

Chang (1994) applied the KLEM model for analyzing the Taiwan manufacturing. The data covers the period from 1956 to 1971, and capital, labor, and energy are assumed as input factors. He compares the results of the tree-level CES (constant elasticity of substitution) function and those of the translog function. He clarified a misconception in Sato's multi-level CES production function. The results supported substitutability between energy and capital.

Caloghirou et al. (1997) analyzes the KLEM model of the Greek manufacturing in 1980s. Capital, labor, electricity, non-electrical energy[1]. The production structure is approximated by the translog model. They compare three types of model, *i.e.*, a static-non-homothetic model (Model 1), a static-homothetic model (Model 2), and a dynamic-homothetic model (Model 3). In the short run,

[1] Non-electrical energy consists of liquid, solid, and gas.

electricity and capital substitutes each other in the Model 2 and Model 3 while they complement in the Model 1. And non-electrical energy and capital substitute each other in all the three models. e, M2 : substitute, M3 : substitute. In a long-term, energy and capital substitute each other regardless of the energy type.

Christopoulos (2000) examines the time series from 1970 to 1990 of the Greek manufacturing by employing the two-stage KLEM model. Capital, labor, and energy are assumed as input factors. Given the approximation by the translog function, they estimated a dynamic production structure as well as a static production structure. In a long-run, capital and energy significantly substitutes each other. Their results are also consistent with the neo-classical theory of production.

Dahl and Erdogan (2000) identified the production structures of the four sector of Turkey from 1963 to 1992: the aggregate economy; the total industry; the total manufacturing; and the mining. Three inputs, *i.e.*, capital, labor, and energy, were supposed to be input factors. They found that own-input demand elasticities to be negative and inelastic for all factors and all sectors. Estimates of cross elasticities suggested that in the inelastic range, capital and labor, as well as capital and energy, are substitute.

Medina and Vega-Cervera (2001) compared the production structures in Italy, Portugal, and Spain from 1980 to 1996 by

applying the KLEM model. Capital, labor, energy are assumed as input factors, and the translog function is utilized for the approximation. In Italy and Spain, energy and capital complemented each other but they substituted in Portugal. They found that the energy and capital are complements in the countries which show high energy independence.

Kuper and van Soest (2003) estimated the KLEM model in the 8 manufacturing sectors in Netherland from 1973 to 1994. They employed the CES (constant elasticity of substitution) function and assumed two inputs, *i.e.*, the intermediate output aggregated by capital and energy, and labor. They found that capital and energy were substitutes before 1986 and have been complements since then. They also discussed that due to the fixed-cost nature of adjustments to relative price changes, these technological parameters are affected by past developments.

Bentzen (2004) analyzed interfactor substitutability in the US manufacturing from 1949 to 1999. Approximated by the translog function, substitutability among capital, labor, energy, and material is derived. The result indicates that energy and capital substitutes each other. In particular, when allowing for asymmetric price effects, the rebound effect is found to be approximately 24% for the US manufacturing sector.

Burki and Khan (2004) considered a method for estimating the effects of allocative inefficiency on resource allocation and energy substitutability. They estimated the extents of mis-allocation of resources and its effects on factor substitutability are estimated by using pooled annual time-series data of the Pakistan's manufacturing. They also estimated the Morishima elasticity of substitution as well as the Allen elasticity of substitution. When the possibility of inefficient allocation was considered, energy and capital substituted each other. And the estimates of the Morishima elasticity of substitution showed that the substitution of capital for energy has been dominant over the substitution of energy for capital in the Pakistan's manufacturing. They found an evidence of allocative inefficiency leading to misspecification of interfactor substitutability.

Cho et al. (2004) analyzes the two-stage production structure in the aggregate economy of South Korea. Unusually, they analyzed quarterly time series data covering from 1981 to 1997. Capital, labor, and energy were assumed as input factor. They estimated a dynamic model as well as a static model. Estimates of both models tell that energy and capital are substitutable. However, the substitytabilty between energy and capital is greater when the dynamic model is applied.

Welsch and Ochsen (2005) estimated the KLEM model for the

manufacturing sector in the West Germany from 1976 to 1994. The KLEM model is approximated by the translog function. Focusing on the difference in labor force, they assumed capital, energy, low-skilled labor, high-skilled labor, and material as input factors. To analyze interfactor substitutability, they estimated the Morishima elasticity of substitution which enables us to find asymmetric substitutability. They concluded that energy substituted capital but capital complemented energy. And while technological change is found to be energy saving, increased openness is energy using, *i.e.*, tends to increase the energy share.

Roy et al. (2006) empirically estimated the KLEM model using the cross-section time series data of the paper, iron and steel, and aggregate manufacturing sectors from 1980 to 1992 in the several developing countries and US. They approximated the KLEM model by the translog function. In the three manufacturing sectors, energy and capital substitute each other generally. The elasticity of substitution between energy and capital ranges from -1.96 to 9.80.

Arnberg and Bjørner (2007) discussed substitutability between energy and capital in depth. They constructed a panel data consisting of the Danish industrial companies. Input factors were assumed to be machine capital, electricity, and other energy. They compared estimates from a translog approximation and those from a linear logit

approximation. The translog estimates tell that electricity and machine capital are substitutable while other energy and machine capital are complementary. However, the linear logit estimates show that all energy inputs are substitutable for machine capital. They raised a possibility that substitutability can be different by energy type.

Feng and Serletis (2008) analyzes the time-series data from 1983 to 2001 of the US manufacturing. They assumed capital, labor, energy, and material as input factors. In particular, they investigate the performance of four flexible functional forms, which describe the production structure. The compared the results derived from the generalized Leontief function, the translog function, the normalized quadratic function, and the globally flexible asymptotically ideal model. Among these functional forms, only the normalized quadratic function and the globally flexible asymptotically ideal model yield theoretically desirable results. The results derived by the normalized quadratic function tell that energy and capital substitutes each other. However, the results derived by the globally flexible asymptotically ideal model tell that energy and capital complements each other.

Ma et al. (2009) analyzed the two-stage translog production structure in China. They constructed a panel dataset covering thirty one provinces from 1995 to 2004. Incorporating capital, labor, and

energy into input factors, their results suggested that energy is substitutable with both capital and labor.

4. 2. Interfuel Substitutability

This section introduces previous literatures on interfuel substitutability by applying the energy sub-model. The energy sub-model is developed and empirically estimated in Fuss (1977) for the first time. He found an explicit link between the energy sub-model which results from the separability restriction and the model explaining the demand for the aggregate inputs. Based on this theory, he examined interfuel and interfactor substitution in Canadian manufacturing.

Kraft and Kraft (1980) proposed to analysis the patterns of fuel choice within the industrial sector by estimating a multiple logit model of fuel choice, using prices and fuel choice experience as explanatory variables. They categorized fuels into nine types. Estimates of price elasticities indicate that electricity demand is only inelastic to price changes, and all fuels substitutes each other.

Considine and Mount (1984) demonstrates a static and dynamic version of a linear logit model, which can apply to analyze interfuel relationships. They showed that there are features of the linear logit model of cost shares that are quite desirable for empirical demand analysis. First, this model guarantees non-negativity of the cost shares, which is a sufficient and necessary condition for non-

negativity of input levels. Second, the model offers a considerable amount of flexibility for empirical applications as well as permits an empirically convenient specification of a dynamic input demand system.

Truong (1985) investigated the two-stage KLEM model in the manufacturing sector of New South Wales (NSW) in Australia. Particularly, he used the absolute price version of the Rotterdam model which is rarely applied. The results indicate that coal is the most substitutable fuel, and the oil demand is the most price-responsive.

Vlachou and Samouilidis (1986) studied interfuel substitutability in the three major sectors of the Greek economy: agriculture; industry; and transport. The major conclusion from the estimates of price elasticity is that electricity demand shows the highest responsiveness to price changes and is the most substitutable one. And all fuels show inelastic price-responsive, which indicates the limited effect of an energy price policy to decrease energy consumption.

Magnus and Woodland (1987) attempted to measure interfuel relationships in six manufacturing industries of Netherlands. They constructed pooled time series data, so the results at a disaggregated industrial level were drawn. They focused on involving both

contemporaneous and inter-temporal correlations between individuals. The results indicate that at the sectoral level, the (conditional) demands for fuels are inelastic with respect to their own prices. They also show that coal and oil are substitute for gas.

Andrikopoulos et al. (1989) address interfuel substitution for the Ontario manufacturing sector using the two-stage KLEM model. Actually, they compared interfuel substitution in seven industries of the manufacturing sectors. Overall, they found that the demand for coal and fuel oil is price-elastic and that for electricity and gas price-inelastic. The results suggest that coal and oil exhibit strong substitutability as compared to that for electricity and gas.

Considine (1989b) examines three possible sources of error in modeling interfuel relationships: the specification of energy substitution groups, the selection of functional form, and the inclusion of regulatory policy variable. First, he found that including non-energy inputs in oil and coal aggregates contribute to incorrect signs. In particular, he suggested a separation of fuel types into three categories: stationary fuel combustion, energy materials, and transport fuels. Second, he asserted that the performance of a linear logit model is better than a translog function from the perspective of concavity and sensibility of estimates of own-price elasticities. Finally, he found that regulatory policy also can be employed as an

explanatory variable of the energy sub-model.

Harvey and Marshall (1991) analyzed interfuel relationships in the UK economy. The distinct point of this study is they modeled factor augmenting technical progress by means of stochastic trend components. Thus, they tried to calculate elaborate forecasts of the future level of energy demand. By their results, electricity and oil demands are highly inelastic to price changes. Also, the technology biases use of fuels towards gas and electricity.

Jones (1995) showed that an extended dynamic linear logit model suggested by Considine (1990) provides theoretical properties superior to a comparable translog model, using annual data on U. S. industrial energy consumption over 1960-1992. Also, he suggested that less 30% of the long-run adjustment occurs in the same year as a price change, with 50% adjustment being attained about halfway through the second year following the year of the price change in U. S. industrial energy consumption. Also he re-confirmed the study of Considine (1989b) which discussed the effects on the estimated price elasticities from excluding non-energy industrial fuels (e.g., coking coal, petrochemical feedstocks, lubricants, etc.), which have very few substitutes.

Using the same data of Jones (1995), Urga (1999) proposed the dynamic formulation of the translog function. Utilizing an error-

correction mechanism (ECM), the results satisfy the concavity condition and yields different interfuel relationships from Jones (1995). The common result of both studies is that coal is the most price-responsive while oil is the least.

Christopoulos (2000) proposed a new version of dynamic translog function in analyzing interfuel relationships. The empirical evidences indicate that interfuel substitution is limited in the case of Greek manufacturing except the high degree of substitution of diesel for electricity. Also, they provide support for inelastic demand for crude oil and electricity.

Bjørner and Jensen (2002) estimated interfuel relationships among electricity, district heating, and other fuels using a micro panel data set containing information for most Danish industrial companies. They found that interfuel substitution is low, and own-price elasticity of electricity is lower than found in previous studies based on macro or micro cross-section data.

Urga and Walters (2003) compare and contrast two dynamic model in analyzing interfuel relationships: a translog function and a linear logit model. The results tell that a dynamic linear logit model is more theoretically plausible. Unlike Jones (1995) and Urga (1999), they addresses that electricity demand is the least price-responsive while gas is the most one.

Park and Na (2004) analyzes the interfuel relationships of energy demand in Korean manufacturing sector using a linear logit model. Their results exhibit that oil demand in inelastic to price change so the Korean manufacturing has been dependent on oil even in a sharp fluctuation of oil price. They also imply that price decline of gas rather than that of coal and oil could be more effective as an energy price policy for the reduction of carbon emissions.

Cho et al. (2004) dealt with interfactor and interfuel relationships in Korea using the two-stage KLEM model. Their results show that interfuel relationships exhibit substantially different patterns after 1989. Oil demand is the least price-responsive and complementarity exists between oil and electricity and coal and electricity. Overall, the magnitude of elasticities is smaller than 1, which indicates inelasticity of fuel demands to price changes.

Ma et al. (2008) tried to combine the analysis of interfuel relationships and decomposition of energy intensity. Firstly, they analyzed interfuel relationships in the China economy using the two-stage KLEM model. The results addresses that coal is significantly substitutable with electricity and complementary with diesel while gasoline and electricity are substitutable with diesel. Through the decomposition analysis, they also found that the major driver of increase in energy intensity is the increased use of energy-intensive

technology.

Serletis et al. (2010a) investigated interfuel relationships in U.S. energy demand by sector (total economy, industrial, commercial, residential, and electricity-generation sectors). For the industrial sector, all own price elasticities are blow unity, and oil demand is inelastically substitutable with other fuels. Moreover, they confirmed that coal, oil, gas, and electricity are weakly separable each other.

Steinbuks (2012) analyzed interfuel relationships for the 15 most energy intensive industries form 1990 to 2007 in the U.K. His study is focused on the comparing interfuel relationships in the aggregate level with that in the disaggregate level., *i.e.*, heating processes. Thus, he tried to address the problem of aggregation across energy use. His results suggest that an increase in energy prices had a limited effect on fuel choice in the heating generation process, with major substitution coming from in fuel demand for energy-using process. In addition, he tried to measure the effect of a rise in energy prices on interfuel substitution by sub-sample analysis.

Combining the results of these previous studies in Table 3.1, fuel demands have shown inelastic responses to price changes in overall. Also, the most price-responsive fuel is coal while there is no consensus on the least price-responsive fuels. Interfuel relationships are different by country, so a common trend in interfuel

substitutability or complementarity is not observed.

Using a pooled international sample of the 20 OECD countries, Griffin (1977) investigated interfuel relationships within the generation of electricity. The main contribution of this study was to test the validity of a translog function in approximating the energy price aggregator. Wide variation in elasticities between countries was observed. In general, his results tell us both that oil seems to be a substitute for gas and that substitution effects between coal and gas tend to be weak.

Pindyck (1979) analyzed interfuel relationships as well as KLEM relationships using the two-stage KLEM model. This was the first study ever to conduct an international comparison of interfuel relationships within the industrial sector. For 10 industrialized countries, Pindyck calculated fuel price elasticities and input factor price elasticities from pooled intercountry data. Through this analysis, he provided evidence for the substitutability of energy and capital. In addition, he showed that it is difficult to find a consensus on fuel price elasticities, except for electricity demand. His results indicated that electricity demand in 10 countries was less elastic than demand for other fuels.

Hall (1983) estimated the energy sub-model for the industrial sector of the seven major OECD countries. With a pooled time series

for 1960–1979, he drew international own-price and cross-price elasticities of fuel demand. His result indicates that gas and coal are relatively price-responsive fuels in spite of oil shocks. Using the same data, he re-examined interfuel relationships for non-energy-producing industrial sectors by country (Hall, 1986). He found own-elasticities of demand for coal and gas to be elastic, those for petroleum products to be somewhat less elastic and sometimes inelastic, and those for electricity to be inelastic. His study shows only a very limited amount of robust evidence on interfuel relationships in general. The results of Hall (1986) are consistent with his former study. However, both studies are limited to dealing with testing the assumptions related to the energy sub-model.

Unlike previous studies employing a translog function, Jones (1996) first applied a linear logit model to carry out an international comparison of interfuel relationships. This study demonstrated an analysis of interfuel substitution possibilities in the industrial sectors of G-7 countries. With pooled intercountry time series data, he obtained long-run price elasticities from pooled intercountry data. The results indicate that the industrial demands for oil and coal are the most elastic, and the strongest channels for interfuel substitution are between oil and natural gas, with no significant evidence of complementarity between fuels.

Using almost the same data as Jones (1996), Renou-Maissant (1999) carried out time series analyses by country, applying a translog function. Her study found more complementary relationships than did Jones (1996). The results outline the weakness of price elasticities over the sample period and show evidence of asymmetric effects. In particular, the inelasticity of energy demand since the collapse of oil prices in 1986 shows evidence of asymmetric effects. The asymmetric effects imply that an irreversible change may have occurred after the oil shocks, and the effects of the shocks were characterized by a certain suspicion of oil.

After the study of Renou-Maissant (1999), there is a void in the literature dealing with international comparison of interfuel relationships. Breaking the silence, Serletis et al. (2010b) demonstrated an investigation of interfuel relationships in 15 developing and industrialized countries. The main contribution of their study was to fill the literature gap by analyzing the case of developing countries. In addition, they examined interfuel relationships in the residential, transportation, and electricity-generation sectors as well as the industrial sector. Contrary to previous studies, they used the globally regular normalized quadratic (NQ) to try to provide a forecast of future interfuel relationships. They also showed that industrial and residential sectors tend to

exhibit higher potential for substitution between energy inputs as compared to the electricity-generation and transportation sectors. In addition, they found that developed countries demonstrate higher potential for interfuel substitution in their industrial and transportation sectors compared to developing economies.

5. Data

This thesis analyzes the structure of production within the following ten OECD countries since 1980: Australia, Austria, Denmark, Finland, Italy, Japan, Republic of Korea (Korea), Netherlands, the United Kingdom (UK), and the United States (US). All these countries are considered by the OECD to be high-income countries that lead the world economy. The reason why these specific countries are selected is data availability. In other words, this thesis analyzes countries where a suitable database for the purposes of the present research exists. The main data sources are the database of the EU KLEMS consortium,[2] the *Energy Balances of OECD Countries* series (IEA, 2011), and the *Energy Prices and Taxes* series (IEA, 2012).

Some features of these countries and their economies are presented in Tables 1~3. Specifically, GDP (gross domestic product), GNI (gross national income) per capita, population, land area, and economic structure are the features included. All data are gathered from the database of the World Bank.[3] In these countries, in recent

[2] http://www.euklems.net

[3] http://data.worldbank.org

years, the proportion of the economy accounted for by the agricultural and industrial sectors has been decreasing, while the proportion accounted for by the service sector has been increasing. Among the 10 countries, Korea has shown the most remarkable economic growth in recent decades. The only countries with a population greater than 100 million are Japan and the US, and the only countries where the land area is greater than one million km^2 are Australia and the US.

Features of the energy systems of these countries are presented in Tables 4~6. Specifically, TPES (total primary energy supply), TFC (total final consumption), TFC of the manufacturing sector, petrochemical feedstock, and index of energy independence the features included. All data are gathered from the database of the *Energy Balances of OECD Countries* series (IEA, 2011). Index of energy independence is defined as the ratio of energy production to TPES, following Medina and Vega-Cervera (2001). The countries included in the study that are highly energy-independent are Australia, Denmark, the Netherlands, the UK, and the US. The index of energy independence in Denmark in particular has increased considerably during the sample period.

Table 1. Economic System of 10 Countries (1985)

	GDP (current million USD)	**GNI per capita (PPP, USD)**	**Population**	**Land area (km^2)**	**Economic Structure (% of value added)**				
					Agriculture	Industry			Service
						Total	Manufacturing	Energy-Intensive	
Australia	181,694	12,580	15,758,000	7,682,300	5.67	38.69	17.84	8.34	55.64
Austria	68,781	14,440	7,564,985	82,450	3.84	37.97	22.51	10.11	58.20
Denmark	61,204	14,370	5,113,691	42,380	5.02	28.56	18.83	6.71	66.42
Finland	54,980	12,690	4,902,206	304,590	7.95	39.22	24.93	11.72	52.84
Italy	435,705	12,800	56,593,071	294,110	4.67	38.59	25.19	9.48	56.74
Japan	1,364,164	12,980	120,754,000	364,600	3.15	41.09	27.79	12.20	55.77
Korea	96,620	4,260	40,806,000	98,730	13.54	29.27	27.30	11.67	57.19
Netherlands	133,245	13,100	14,491,632	33,760	4.14	34.90	17.75	8.44	60.96
UK	464,268	11,770	56,550,268	241,930	1.73	38.96	23.75	10.22	59.32
US	4,184,800	17,520	237,924,000	9,158,960	2.42	33.23	19.48	8.06	64.36

Table 2. Economic System of 10 Countries (1995)

	GDP (current million USD)	**GNI per capita (PPP, USD)**	**Population**	**Land area (km^2)**	**Economic Structure (% of value added)**				
					Agriculture	Industry			Service
						Total	Manufacturing	Energy-Intensive	
Australia	371,091	20,140	18,072,000	7,682,300	3.42	28.97	14.58	7.06	67.61
Austria	238,562	23,180	7,948,278	82,450	2.63	30.73	19.34	8.34	66.65
Denmark	181,984	22,750	5,233,373	42,380	3.47	25.08	17.12	6.86	71.45
Finland	130,806	18,200	5,107,790	304,590	4.48	33.29	25.28	12.94	62.23
Italy	1,126,041	20,890	56,844,303	294,110	3.31	30.28	22.23	9.36	66.42
Japan	5,264,380	22,740	125,439,000	364,600	1.89	34.34	23.31	10.01	63.77
Korea	517,118	12,420	45,093,000	98,730	6.35	41.85	27.61	12.02	51.80
Netherlands	418,969	21,890	15,459,006	33,760	3.48	27.36	17.44	8.72	69.16
UK	1,157,119	19,580	58,019,030	241,930	1.84	31.00	21.27	9.70	67.16
US	7,338,400	27,550	266,278,000	9,158,960	1.61	26.31	17.71	7.82	72.08

Table 3. Economic System of 10 Countries (2005)

	GDP (current million USD)	**GNI per capita (PPP, USD)**	**Population**	**Land area (km^2)**	**Economic Structure (% of value added)**				
					Agriculture	Industry			Service
						Total	Manufacturing	Energy-Intensive	
Australia	696,034	31,540	20,394,800	7,682,300	3.27	26.77	11.02	5.51	69.96
Austria	304,984	33,300	8,227,829	82,450	1.61	29.26	19.39	8.73	69.13
Denmark	257,676	33,660	5,419,432	42,380	1.43	25.51	14.18	6.14	73.06
Finland	195,778	30,850	5,246,096	304,590	2.77	32.45	23.04	10.36	64.78
Italy	1,777,694	28,290	58,607,043	294,140	2.20	26.87	18.49	7.76	70.93
Japan	4,552,200	31,030	127,773,000	364,500	1.53	30.45	21.17	9.13	68.02
Korea	844,863	22,760	48,138,000	96,850	3.33	37.70	28.34	12.23	58.96
Netherlands	638,471	35,270	16,319,868	33,760	2.09	24.17	14.28	7.26	73.74
UK	2,280,114	33,290	60,224,307	241,930	0.67	23.47	13.26	6.04	75.85
US	12,579,700	43,170	295,516,599	9,161,920	1.21	22.14	13.65	6.54	76.65

Table 4. Energy System of 10 Countries (1985)

	TPES (kTOE)	**TFC (kTOE)**						**Petrochemical feedstock (kTOE)**	**Energy Independence**
			Manufacturing (kTOE)						
				Coal (%)	Oil (%)	Gas (%)	Electricity (%)		
Australia	72,824	49,311	15,986	26.35	10.75	27.82	21.51	1,288	1.76
Austria	23,085	18,968	4,612	24.98	10.52	26.78	30.77	511	0.33
Denmark	19,300	14,233	2,510	10.08	54.02	4.50	23.51	0	0.26
Finland	25,834	18,987	7,769	17.97	18.02	5.79	29.09	443	0.40
Italy	129,304	100,662	29,950	14.45	33.14	26.02	26.03	3,643	0.18
Japan	362,906	241,236	86,049	26.03	37.54	3.18	30.51	17,149	0.18
Korea	53,528	38,227	10,127	20.11	53.42	0.00	26.48	3,156	0.27
Netherlands	60,639	50,531	11,786	9.02	18.23	52.38	20.38	4,126	1.09
UK	200,785	133,196	33,200	22.94	16.80	39.51	20.76	5,241	1.19
US	1,774,101	12,693,801	340,816	13.97	18.72	36.48	18.53	42,608	0.88

Table 5. Energy System of 10 Countries (1995)

	TPES (kTOE)	**TFC (kTOE)**						**Petrochemical feedstock (kTOE)**	**Energy Independence**
			Manufacturing (kTOE)						
				Coal (%)	Oil (%)	Gas (%)	Electricity (%)		
Australia	92,556	62,155	18,431	22.44	6.97	34.05	27.16	2,203	2.02
Austria	26,696	21,234	4,997	10.57	11.71	32.82	31.26	562	0.33
Denmark	19,392	14,508	2,743	10.90	25.05	27.93	28.29	0	0.80
Finland	28,920	22,297	9,245	13.42	9.93	10.08	33.09	585	0.46
Italy	159,131	120,510	33,779	8.05	17.67	43.66	29.87	5,473	0.18
Japan	496,247	331,691	94,480	29.66	31.48	4.85	31.59	29,010	0.20
Korea	144,756	104,683	28,676	21.07	46.73	1.86	27.61	15,547	0.15
Netherlands	70,748	53,613	12,599	6.52	7.14	51.03	24.52	4,926	0.94
UK	216,264	143,668	30,292	15.04	17.07	38.10	28.07	6,762	1.19
US	2,067,213	1,377,694	68,896	10.26	9.65	41.69	32.16	74,240	0.80

Table 6. Energy System of 10 Countries (2005)

	TPES (kTOE)	**TFC (kTOE)**						**Petrochemical feedstock (kTOE)**	**Energy Independence**
			Manufacturing (kTOE)						
				Coal (%)	Oil (%)	Gas (%)	Electricity (%)		
Australia	119,592	75,468	21,984	16.23	6.28	34.74	31.13	1,230	2.34
Austria	33,951	27,901	6,704	7.71	5.77	35.61	31.01	614	0.30
Denmark	18,889	14,915	2,589	8.23	21.40	26.81	32.87	0	1.66
Finland	34,224	25,524	11,075	8.79	9.53	6.49	32.90	559	0.49
Italy	183,873	138,725	37,986	6.61	16.64	36.40	32.14	4,050	0.15
Japan	520,515	346,943	92,629	31.10	28.36	6.30	31.48	33,631	0.19
Korea	210,102	140,151	37,986	17.09	19.25	10.97	41.35	28,401	0.20
Netherlands	78,824	60,366	13,586	4.57	14.46	40.88	25.64	8,770	0.79
UK	222,364	149,355	31,189	6.66	21.74	36.90	31.46	6,165	0.92
US	2,318,861	1,569,696	281,138	10.24	11.90	38.05	27.47	85,329	0.70

TEORETICAL MODEL: KLEM MODEL

1. KLEM Model

1. 1. KLEM Model and Cost Function Approach

The KLEM Model indicates idiomatically the analysis of a production technology containing inputs of capital (K), labor (L), energy (E) and material (M). It starts from considering a twice-differentiable production functions with n inputs:

$$Y = f(\boldsymbol{x}) = f(x_1, \ldots, x_n), \quad x_i > 0. \tag{1}$$

Y is maximum possible output from any given set of inputs, $\boldsymbol{x} = [x_1, \ldots, x_n]$ where the i-th input, x_i ($i = 1, \ldots, n$) is weakly separable each other. A production function $f(\cdot)$ means a producer's technology that combines inputs most efficiently. In the framework of the KLEM model, the output is represented as a function of the four input quantities. This is the most general form of the KLEM model and is defined as follows:

$$Y = f(\boldsymbol{x}) = f(x_K, x_L, x_E, x_M), \quad x_i > 0. \tag{2}$$

Technological restrictions are manifested in the economic behavior of optimizing agents in the above production function. In reality, they are hard to be observed. The dual approach is an attempt to overcome this obstacle. Shephard (1953) asserted that the dual approach describes the production technology in terms of the cost function solely. The principle of duality states that we can reconstruct the properties of the production technology by analyzing the indirect dual function, *i.e.*, cost function. The premise of the dual approach is to satisfy some regularity conditions[4].

When Y and input prices are exogenous, the cost-minimization assumption implies the existence of a cost function dual to $f(\cdot)$,

$$C = g(p_1, \ldots, p_n, Y), \quad i = K, L, E, M . \tag{3}$$

$\boldsymbol{p} = [p_K, p_L, p_E, p_M]$ is a vector of strictly positive input prices. Eq. (3) indicates a cost function which represents the minimum cost of producing a given output level Y during a given time period.

[4] The regularity conditions are non-negativity and zero-degree homogeneity in prices of the derived input demand and negative semi-definiteness of the Hessian matrix. These regularities are described in the Section 1. 2. of this chapter.

That is, the minimum cost is expressed as a function of input prices and output. When a cost function shown in Eq. (3) is empirically estimated, a form of $g(\cdot)$ is approximately determined by flexible functional forms[5].

In general, estimation of the corresponding cost function instead of a production function is more preferred especially in case of analyzing a production technology at aggregate level. Binswanger (1974) explains several advantages of using a cost function rather than a production function for estimating production technology as follows. First, it is not necessary to impose homogeneity of degree one on the production process because a cost function is homogenous in prices in regardless of the homogeneity problem of the production functions. Second, input quantities are not proper exogenous variables. Actually, input quantities are the result of a producer's decision making based on input factor prices. Third, if a production function is used to derive elasticities of substitution in the many-factor case, the matrix of production function coefficients has to be inversed. This procedure can yield estimation error and moreover, no solution. Fourth, high multi-collinearity among the input variables

[5] The Section 3 of this chapter will explain the definition of a flexible functional form and a variety of types of flexible functional forms.

often causes biased estimates of a production technology. Since there is usually little multi-collinearity among factor prices, this problem does not arise in estimation of the corresponding cost function.

1. 2. Properties of Cost Function and Derived Input Demand

The main contribution of duality is being able to use a cost function to describe accurately a production technology. That is, a specification of a well-behaved cost function is equivalent to the specification of a well-behaved production function. McFadden (1978) even mentioned that a corresponding cost function is a "sufficient statistic" for a production technology since all economically relevant information about the technology can be gleaned from the cost function. Moreover, a cost function also gives information on the properties of derived input demands.

If the underlying production function, $f(\boldsymbol{x})$, satisfies 1) monotonicity, 2) weak essentiality, 3) existence for all finite $\boldsymbol{x}$, and 4) quasi-concavity, the cost function defined by Eq. (3) will satisfy the following six properties. In fact, these properties can be shown to be sufficient conditions for the existence of the corresponding cost function, $C(\boldsymbol{p}, Y)$ (Varian, 1992).

- Non-negativity: $C(\boldsymbol{p},Y)>0$ for $\boldsymbol{p}>0$ and $Y>0$
- Monotonicity in $\boldsymbol{p}$: if $\boldsymbol{p}'\geq\boldsymbol{p}$, then $C(\boldsymbol{p}',Y)\geq C(\boldsymbol{p},Y)$
- Concave and continuous in $\boldsymbol{p}$
- Linear homogeneity in $\boldsymbol{p}$: $C(k\boldsymbol{p},Y)=kC(\boldsymbol{p},Y)$, $k>0$
- Non-decreasing in Y: if $Y'\geq Y$, then $C(\boldsymbol{p},Y')\geq C(\boldsymbol{p},Y)$
- No fixed costs: $C(\boldsymbol{p},0)=0$ [6]

When the cost function is differentiable in $\boldsymbol{p}$, we can derive a unique vector of cost-minimizing input demands, $x_i(\boldsymbol{p},Y)$, by the Shephard's lemma. This lemma is defined as:

- Shephard's lemma: Let $x_i(\boldsymbol{p},Y)$ be the firm's conditional factor demand for input i. Then if the cost function is differentiable at $(\boldsymbol{p},Y)$, and $\mathrm{p_i}>0$ for $i=K,L,E,M$, then $x_i(\boldsymbol{p},Y)=\dfrac{\partial C(\boldsymbol{p},Y)}{\partial p_i}$.

Thus, the behavior of the derived conditional input demands is determined by that of the cost function. Properties that the conditional input demand functions $x_i(\boldsymbol{p},Y)$ should exhibit the

[6] This assumption implies that we are dealing with a long-run cost function.

following three conditions (Varian, 1992).

- Non-negativity: $x_i(\boldsymbol{p}, Y) \geq 0$
- Zero-degree homogeneity in prices: $x_i(k\boldsymbol{p}, Y) = x_i(\boldsymbol{p}, Y)$
- The following matrix, $D^2_{pp}C(\boldsymbol{p}, Y) = \nabla_p x(\boldsymbol{p}, Y)$ is negative semi-definite and symmetric

As with the cost function, these properties are sufficient conditions for the existence of well-behaved demand functions (Considine and Mount, 1984). In other words, if a set of functions exhibits these properties, then the functions may be used to represent the derived input demand functions. Particularly, the third property of the conditional demand functions is the sufficient and necessary conditions for the concavity of the cost function, and it has following three implications.

- By Young's theorem, the cross price effects are the same:

$$\frac{\partial x_i(\boldsymbol{p}, Y)}{\partial p_j} = \frac{\partial^2 C(\boldsymbol{p}, Y)}{\partial p_i \partial p_j} = \frac{\partial^2 C(\boldsymbol{p}, Y)}{\partial p_j \partial p_i} = \frac{\partial x_j(\boldsymbol{p}, Y)}{\partial p_i}$$

- The own-price effects are non-positive: $\frac{\partial x_i(\boldsymbol{p}, Y)}{\partial p_i} = \frac{\partial^2 C}{\partial p_i^{\,2}} \leq 0$

- The property of negative semi-definiteness could be confirmed given symmetry by determining that none of the eigenvalues of the matrix are positive.

2. Energy Sub-Model

2. 1. Energy Sub-Model

The energy sub-model, established by Fuss (1977), solely consider a producer's decision on a cost minimizing choice of energy mix. The primary premise of this model is weak separability in energy and other input factors, such as capital, labor, and material. That is, a cost-minimizing choice of energy mix is independent of the optimal mix and level of labor, capital, and material, even though the level of total energy use is not. If homothetic weak separability is imposed on the production function is defined as Eq. (2), the production function will be re-written as

$$Y = f(x_K, x_L, x_E(x_{E1}, \ldots x_{EL}), x_M), \quad \forall x_i > 0. \tag{4}$$

x_E , the total energy measure, is an appropriately chosen homothetic aggregator function. It will not be a simple sum of TOE (ton of equivalents) unless the energy components, x_{El} $(l = 1, \ldots, L)$, are perfect substitutes or complements in the production process (Nguyen, 1987). By the duality theorem (Shephard, 1953), the cost function corresponding to Eq. (4) is also weakly separable and is

defined as

$$C = g[p_K, p_L, p_E(p_{E1}, \ldots, p_{EL}), p_M, Y]. \quad (5)$$

$p_E(\cdot)$ is an energy price aggregator function, and p_{El} ($l = 1, \ldots L$) are the prices of energy components. $p_E(\cdot)$ is not equal to a simple weighted average of the p_{El}, unless the x_{El} are not perfect substitutes or complement. Here, $p_E(p_{E1}, \ldots, p_{EL})$ is the most general form of the energy sub-model.

2. 2. Two-Stage KLEM Model

The two-stage KLEM Model is a combination of the KLEM model and the energy sub-model. In the two-stage KLEM model, the energy price aggregator, $p_E(\cdot)$, is estimated by the energy sub-model at the first stage. Then, with substituting $p_E(\cdot)$ for p_E in Eq. (3), a cost function of a producer is estimated at the second stage[7] (Fuss, 1977; Pindyck, 1979). The necessary and sufficient condition of the two-stage KLEM model is weak separability and homogeneity in

[7] The two-stage KLEM model is applicable to not only energy input but also the other inputs.

energy input (Fuss, 1977). The two-stage KLEM model enables us to model how an individual price of energy component affects its consumption through the feedback effect between interfuel and interfactor substitutability (Cho et al., 2004).

When the two-stage KLEM model is estimated, a translog function (Christensen et al., 1973) is mostly applied. The main reason of using a translog function is that it is actually used to approximate Divisia aggregation, which is known as having a number of desirable properties as an aggregation procedure (Diewert, 1976). Applying a translog function, the energy price index, $\hat{p}_E$, is generated form the first stage;

$$\log \hat{p}_E = \alpha_0 + \sum_i \alpha_i \log p_{Ei} + \frac{1}{2}\sum_i \sum_j \beta_{ij} \log p_{Ei} \log p_{Ej}, \quad \forall i, j = 1, \ldots, L \tag{6}$$

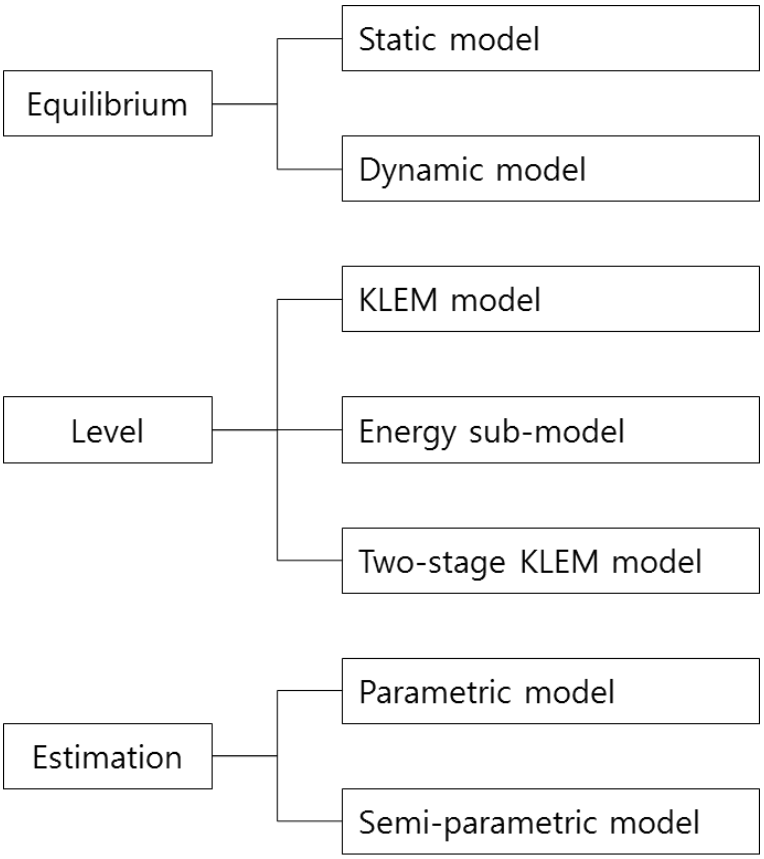
Utilizing $\hat{p}_E$ as an instrumental variable, the KLEM model is estimated at the second stage as follows

$$\log C = \alpha_0 + \alpha_Y \log Y + \sum_i \alpha_i \log p_i + 1/2\,\beta_{YY} (\log Y)^2 + 1/2 \sum_i \sum_j \beta_{ij} \log p_i \log p_j + \sum_i \beta_{Yi} \log Y \log p_i \,. \tag{7}$$

3. Model Specification

The KLEM model can be specified based on the three criteria. In Figure 2, the specification of the KLEM model by the criteria is graphically presented.

Figure 2. Specification of the KLEM Model



First, the KLEM model can be specified by the object of analysis. Then, it is classified into the KLEM model, the energy sub-model,

and the two-stage KLEM model (Berndt and Wood, 1975; Diewert, 1971; Fuss, 1977; Pindyck, 1979). This classification has been already described in Section 1 and 2 of this chapter.

Second, the KLEM model can be specified as a static model and a dynamic model by the perspective of defining equilibrium. A static model assumes the coincidence of a short-term equilibrium and a long-term equilibrium. However, when the static KLEM model is analyzed by using time-series data, it can yield a biased estimator. It eventually analyzes a long-term equilibrium although the time-series data includes a short-term adjustment in the production structure.

The dynamic KLEM model can analyzes separately a short-term adjustment process and a long-term equilibrium (Berndt et al., 1977; Pindyck and Rotemberg, 1983). In other words, it allows us to describe a producer's decision that uses all available information to choose both flexible and quasi-fixed inputs over time. In the dynamic KLEM model, the objective of a producer is to maximize the expected present discounted value of the flow of net revenue, given possible uncertainty over the evolution of input and output prices (Pindyck and Rotemberg, 1983). However, the estimation of a dynamic model is so complicated that features, such as elasticities, are hard to be derived. In general, the dynamic model includes a lagged term of a dependent variable, *i.e.*, cost, as follows (Anderson

and Blundell, 1982).

$$C = g(p_1, \ldots, p_n, Y, C_{t-1}), \quad i = K, L, E, M \tag{8}$$

Third, the model can be specified as the parametric model and the semi-parametric model by the assumption on the error terms. The cost function $g(\cdot)$ shown in Eq. (3) is generally approximated by a parametric functional form, e.g. a flexible functional form. If error terms $\boldsymbol{\varepsilon} = [\varepsilon_1, \ldots, \varepsilon_n]$, which cannot be fully explained by $g(\cdot)$, is supposed to follow a non-parametric distribution function, the model is defined as the semi-parametric one (Feng and Serletis, 2008). A distribution function of error terms is usually estimated by using a kernel smoother (Hastie et al., 2008) or the optimization procedure (Burguete et al., 1982). If they are supposed to follow a parametric distribution function, e.g. a normal distribution function, the model is defined as the parametric one. Most studies have analyzed the parametric KLEM model. There also exist some literatures focusing on the econometric issues analyzed the semi-parametric KLEM model (Feng and Serletis, 2008; Gallant and Golub, 1984).

4. Elasticity of Substitution

The elasticity of substitution, σ, was originally defined by Hicks (1932). It tells the proportionate change in the ratio of input factors employed divided by the proportionate change in the ratio of their prices under conditions of perfect competition. Hicks's key insight was that the effect of changes in the factor price ratio for a given output can be completely characterized by a scalar measure of curvature of the isoquant. However, the Hicks's idea has a defect that it is only applicable to when there exist only two inputs because it does not allow for optimal adjustment of all inputs to a change in a price ratio (Chambers, 1988). If σ in positive, then two inputs substitutes each other. If σ is negative, then they are complements. The original definition of elasticity of substitution by Hicks (1932) can be written as

$$\sigma \equiv \frac{d \ln(x_2 / x_1)}{d \ln(f_1 / f_2)} = \frac{d \ln(x_2 / x_1)}{d \ln(w_1 / w_2)} . \qquad (9)$$

To rectify the inadequacy of Hicks' definition, alternative forms of elasticity of substitution have been demonstrated as follows: Allen/Uzawa elasticity of substitution (AES), Morishima elasticity of

substitution (MES), and shadow elasticity of substitution (SES). Following Chambers (1988), AES, MES, and SES correspond the concept of one-price-one-factor elasticities of substitution (OOES), two-factor-one-price elasticities of substitution (TOES), and two-factor-tow-price elasticities of substitution (TTES), respectively. Mundlak (1968) demonstrated that OOES, TOES, and TTES can be expressed as the following forms:

- OOES: $\frac{d \ln x_i}{d \ln p_j}$
- TOES: $\frac{d \ln x_i - d \ln x_j}{d \ln p_j}$
- TTES: $\frac{d \ln x_i - d \ln x_j}{d \ln p_j - d \ln p_i}$

First, the AES (Allen, 1938) generalizes Hicks's idea for n inputs, and defined the partial elasticity of substitution σ_{ij}^a for inputs i and j. Applying the dual relationships between cost and production functions, σ_{ij}^a can be defined in terms of the cost function (Uzawa, 1962). It is considered as a kind of OOES since it is just a cross-price elasticity divided by cost share. The AES is expressed as

$$\sigma_{ij}^{a} = C\frac{\partial^2 C/\partial p_i \partial p_j}{\left(\partial C/\partial p_i\right)\left(\partial C/\partial p_j\right)} = \frac{\eta_{ij}}{S_j}, \tag{10}$$

where S_j denotes cost share of j-th input and η_{ij} cross-price elasticity between i-th and j-th inputs.

Second, the MES (Blackorby and Russell, 1989; Morishima, 1967), which is a scalar measure of curvature in more than two inputs, is developed. The MES σ_{ij}^{m} is defined as a logarithmic derivative of the optimal input quantity ratio with respect to the input price ratios. It is regarded as a TOES because it yields an exact measure of how the ratio of i-input to j-input responds to a change in p_j. The MES is defined as:

$$\sigma_{ij}^{m} = \frac{p_i\left(\partial^2 C/\partial p_i \partial p_j\right)}{\partial C/\partial p_j} - \frac{p_i\left(\partial^2 C/\partial^2 p_i\right)}{\partial C/\partial p_i} = \eta_{ji} - \eta_{ii}. \tag{11}$$

The MES is sign asymmetric unlike the AES. That is, the classification whether they are Morishima substitutes or complements

depends on which input price changes. If inputs are Allen substitutes, then they are also Morishima substitutes[8] but the opposite direction is ambiguous. Meanwhile, if they are Morishima complements, they are also Allen complements but the reverse is ambiguous. In general, the MES tends to indicate more inputs as substitutes than the AES.

Third, the SES (McFadden, 1963) was suggested at the level of TTES. The SES measures how input ratios respond to price changes along a given factor price frontier at constant cost. The SES σ_{ij}^{s} is a weighted average of two MESs where the weights are given by the relative cost shares. Thus the SES yields not only a symmetric version of the MES but also TTES, *i.e.*, a more complete measure of relative input responsiveness. It is expressed as:

$$\sigma_{ij}^{s} = \frac{S_i}{S_i + S_j}\sigma_{ij}^{m} + \frac{S_j}{S_i + S_j}\sigma_{ji}^{m}. \tag{12}$$

Although the AES is most common in empirical work for its simplicity and symmetry (Stern, 2011), Blackorby and Russell (1989)

[8] Assuming negative own-price elasticities, this explanation is valid. This assumption is quite reasonable since the negative own-price elasticities correspond to the law of demand.

showed that the MES is the theoretically correct measure in the multi-input case. Following their opinions, the AES does not preserve the salient characteristics of the Hicks's original notion. In detail, they showed that the AES fails to measure the curvature of the isoquant and provides no information about relative factor share. Also, the AES is uninformative than price elasticity. It is noticeable that they asserted that in the case of more than two inputs, asymmetry is natural as the partial derivative of cost function must be evaluated in the direction of the input price that actually changes. Based on their contention, symmetric elasticities of substitution, such as the AES and SES, distort the actual curvature of the isoquant. Moreover, Stiroh (1999) empirically showed that the AES can give a misleading picture of substitution behavior. However, Christev and Featherstone (2009) showed that the AES allows for the verification of curvature properties. Thus, an agreement on the issue that which kind of elasticity of substitution is appropriate has not been reached. That is, the kind of elasticity of substitution should be selected by the objective of analysis.

5. Flexible Functional Form

A flexible functional form has been widely applied to empirically estimate of the KLEM model. A flexible functional form portrays features of a production technology without imposing any constrains on the level of cost, the derived demand, and matrix of derived-demand elasticities (Barnett and Binner, 2004; Diewert, 1971). So a flexible functional form is distinguished from the Cobb-Douglas function, the Leontief function, and the constant elasticity of substitution function. In contrast to these functions, a flexible functional form makes no restrictive assumptions on the estimated substitution elasticities, and on the optimal path of input factor adjustments induced by price changes.

For any arbitrary cost function $h^*(z)$, a twice-continuously function approximated by a flexible functional form $h(z)$ ensures satisfaction of the following conditions,

$$\begin{aligned} &h^*\left(z^0\right) = h\left(z^0\right) \\ &\nabla_z h^*\left(z^0\right) = \nabla_z h\left(z^0\right) \\ &\nabla_{zz} h^*\left(z^0\right) = \nabla_{zz} h\left(z^0\right) \end{aligned} \quad . \qquad (13)$$

That is, the parameters of $h(z)$ can be chosen such that its

function value, gradient, and Hessian matrix equal the corresponding magnitudes for any arbitrary $h^*(z)$ at z^0. For an n-dimensional input vector, the conditions presented in Eq. (13) are converted to the following condition; the number of parameters of a flexible functional form approximating a well-defined technology should be greater than $(n+1)(n+2)/2$. In addition, Eq. (13) indicates that a flexible functional form can be drawn by an arbitrary second-order approximation of a cost function.

There are a bunch of flexible functional forms, and some of them are as follows: a transcendental logarithmic (translog) function (Christensen et al., 1973); a generalized Leontief (Diewert, 1971); a generalized Box-Cox (GBC) model (Berndt and Khaled, 1979); a linear logit model (Theil, 1969); a generalized McFadden (Diewert and Wales, 1987); a minflex-Laurent function (Barnett, 1985); a asymptotic ideal model (AIM) (Barnett et al., 1991), etc.

Putting together the discussions on comparing performance of different flexible functional forms (Caves and Christensen, 1980; Diewert and Wales, 1987; Feng and Serletis, 2008; Guilkey et al., 1983; Manera and Sitzia, 2005; Ryan and Wales, 2000), the following criteria should be checked to confirm that the estimated cost function describes a well-behavior production technology. First, whether the estimate of the cost function satisfies the economic regularity is

checked. Here, concavity, monotonicity, and homogeneity in price of the cost function are regarded as the economic regularity. Barnett (2002) referred that if these regularities are violated, the duality between a production function and a cost function may not be established. Thus, a violation of the regularities raises a potential misspecification of a production technology. Second, the econometric regularity is checked. Since the estimation accompanies econometrics, we should consider whether the parameter estimates are econometrically reliable. Namely, R^2 figure and autocorrelation should be reviewed.

The most popular flexible functions are a translog function and a generalized Leontief function (Dumont, 2006). However, both models fail concavity conditions within the data region (Barnett et al., 1985; Berndt and Wood, 1979; Diewert and Wales, 1987). A generalized Leontief function tends to satisfy concavity when substitutability is low while a translog function does when elasticity of substitution is close to one (Guilkey et al., 1983). Despite of violating regularities, the two functions are frequently applied because of their simplicity.

6. Econometric Estimation of the KLEM Model

Estimation of an approximated cost function using an ordinary least square technique requires a large number of observations. It also yields multi-collinearity and decrease in the degree of freedom of the model. Instead, a system of equations by applying the Shephard's lemma to the cost function can be estimated. Zellner (1962) suggested an econometric method to estimate a system of equations and it is applicable to estimate parameters of the KLEM model. It is named as seemingly unrelated regression, abbreviated as SUR. This section introduces the SUR, which is the main estimation technique of the thesis.

Suppose the following system of n equations.

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} = \begin{bmatrix} X_1 & & & \\ & X_2 & & \\ & & \ddots & \\ & & & X_n \end{bmatrix} \begin{bmatrix} \beta_1 \\ \beta_2 \\ \vdots \\ \beta_n \end{bmatrix} + \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_n \end{bmatrix} \tag{14}$$

The SUR assumes the following four conditions on disturbance terms of the above Eq. (14).

- $E(u_{it} \mid X_t) = 0$
- $Var(u_{it} \mid X_t) = E(u_{it}^2 \mid X_t) = \sigma_i^2$
- $Cov(u_{it}u_{jt} \mid X) = E(u_{it}u_{jt} \mid X) = \sigma_{ij}$
- $Cov(u_{it}u_{js} \mid X) = E(u_{it}u_{js} \mid X) = 0$

The second assumption means the variance of a disturbance is constant over the observations while it varies over equations. The third assumption presents contemporaneous correlation of disturbances over equations. Finally, the fourth assumption indicates no serial correlation across time. In sum, $E(u_i \mid X) = 0$ and $E(u_i u_j' \mid X) = \sigma_{ij} I_T$. The covariance matrix of the complete disturbance vector is given by

$$\boldsymbol{\Phi} = E(uu') = \begin{bmatrix} \sigma_{11}I_T & \sigma_{12}I_T & \cdots & \sigma_{1n}I_T \\ \sigma_{21}I_T & \sigma_{22}I_T & \cdots & \sigma_{2n}I_T \\ \vdots & \vdots & \ddots & \\ \sigma_{n1}I_T & \sigma_{n2}I_T & \cdots & \sigma_{nn}I_T \end{bmatrix} = \boldsymbol{\Sigma} \otimes I_T . \qquad (15)$$

Assuming positive definiteness of the matrices $\boldsymbol{\Sigma}$ and $\boldsymbol{\Phi}$, a matrix, $\boldsymbol{P}$ subject to $P\Phi P' = I_{NT}$ always exists. Thus, the variance-covariance matrix of disturbances can be re-written as

$$E(u^* u^{*\prime}) = I_{NT}, \quad where \quad u^* = Pu . \tag{16}$$

Thus, the elements of the transformed disturbance vector u^* are uncorrelated and have identical estimators. Then, the least squares estimator $\hat{\beta} = (X^{*\prime} X^*)^{-1} X^{*\prime} y^*$ is the best unbiased, where $X^* = PX$ and $y^* = Py$. Here is the problem that the $\boldsymbol{\Sigma}$ is unknown in reality. So a disturbance u_i is replaced with $\varepsilon_i = y_i - X_i b_i$, where $b_i = (X_i' X_i)^{-1} X_i' y$. Then, consistent estimate of the variances and covariance are given by

$$\hat{\sigma}_{ij} = \frac{1}{T} \varepsilon_i' \varepsilon_i . \tag{17}$$

T is the number of observations. $\hat{\sigma}_{ij}$ substitutes σ_{ij} in Eq. (15) and then, $\boldsymbol{\Sigma}$ is redefined as $\hat{\boldsymbol{\Sigma}}$. The corresponding estimator for $\hat{\beta}$ with $\hat{\boldsymbol{\Sigma}}$ is the SUR estimator. Alternatively, we can estimate $\hat{\sigma}_{ij}$ and $\hat{\beta}$ in an iterative way until convergence and then, $\hat{\beta}$ is named as the iterative seemingly unrelated regression estimator.

PART I. SEPARABILITY BETWEEN CAPITAL AND ENERGY AGGREGATES

1. Introduction

The real production process includes dozens of input factors. An analysis of a production structure with considering all relevant input factors is practically impossible because of data availability as well as complexity of interpretation. Thus, in many applied studies of the KLEM model, aggregate input indices are used within the theoretically permissible range. The key concept of the input aggregation is separability (Chambers, 1988; Leontief, 1947). Since Berndt and Wood (1975) proposed the KLEM model, many studies describing a production technology of the industrial sector have assumed that various inputs are integrated into capital (K), labor (L), energy (E), and material (M), based on separability.

Separability can be explained as follows. Suppose that a production structure is separated into several different levels. Then, an intermediate good is produced at each level, refers to the integration process which is production function of this intermediate good. The final production process is defined as a function that produce a final output using the intermediate goods at just before the

final level. If the production processes of intermediate goods are separable from each other, input factors of the final production function are defined as these separable intermediate goods. That is, the assumption of separability simplifies complicated production process and thus is very useful in application of KLEM model.

However, separability does not explain the integration of different energy sources in the industrial sector well. If energy is separable from other inputs, such as capital, labor, and material, the integration of energy sources will be determined by price changes in energy sources. On the other hand, what type of capital asset is invested is closely related with the choice of energy source in the industrial sector. That is to say, the capital investment may have influence on the integration process of energy sources. This possibility implies that the assumption of separability between energy and capital deviated from the theoretically permissible range.

The issue of separability between energy and capital was firstly discussed in the study of Fuss (1977). He admitted that the energy mix results from the investment choice of capital assets. Nevertheless, he asserted that the conditions for separability are satisfied because capital assets are usually measured in monetary units regardless of their different types. However, Field and Grebenstein (1980) and Garofalo and Malhotra (1988) showed that substitutability between

energy and capital is different by capital type. Ilmakunnas and Törmä (1989) and Kim and Heo (2010) showed that substitutability between energy and capital is also different by energy type. These studies imply indirectly that energy may be not separable from capital.

This part firstly investigates the adequacy of assuming separability between energy and capital using the data of manufacturing sectors in the ten OECD countries. The method suggested by Denny and Fuss (1977), *i.e.*, a representative way to test separability (Serletis et al., 2010a), is applied. If the assumption of separability between energy and capital is not appropriate, it will be better to divide energy and capital into sub-inputs at the possible level.

The remainder of the Part I is organized as follows. In the next section, the theoretical definition of separability assumption and Denny and Fuss (1977)'s method for separability test are introduced. Section 3 explains the framework for separability test between energy and capital in this thesis. Section 4 describes data used in the analysis, and Section 5 demonstrates the test results. Finally, the findings are summarized in Section 6.

2. Separability

2. 1. Definition of Separability

Since the concept of separability was demonstrated in 1940s by Leontief (1947), many researchers have commented about separability (Green, 1964; Solow, 1955; Strotz, 1959). The microeconomic definition of separability, which has been applied until these days, was established by Berndt and Christensen (1973).

Suppose a twice-differentiable, strictly quasi-concave homothetic production function with a finite number of inputs, each having a strictly positive marginal product. This production function is denoted as $f(X)$. The set of n inputs $N=[1,\ldots,n]$ is partitioned into r mutually exclusive and exhaustive subsets $[N_1,\ldots,N_r]$, a partition which is called as R.

The production function $f(X)$ is weakly separable with respect to the partition R if the marginal rate of substitution (MRS) between any two inputs x_i and x_j from any subset x^s $(s=1,\ldots,r)$ is independent of the quantities of inputs outside of x^s. This imposition is mathematically represented as

$$\frac{\partial}{\partial x_k}\left(\frac{\partial f / \partial x_i}{\partial f / \partial x_j}\right) = 0, \text{ for all } \; i, j \in N_s, \text{ and } \; k \notin N_s. \qquad \text{(I-1)}$$

Weak separability with respect to the partition R is necessary and sufficient for defining the production function $f(X)$ to be the from $f(x^1, x^2, \ldots, x^r)$, where x^s is a function of the elements of N_s.

The production function $f(X)$ is strongly separable with respect to the partition R if the MRSs between any two inputs from subsets N_s and N_t do not depend on the quantities of inputs outside of N_s and N_t. It is represented as

$$\frac{\partial}{\partial x_k}\left(\frac{\partial f / \partial x_i}{\partial f / \partial x_j}\right) = 0, \text{ for all } \; i \in N_s, \quad j \in N_t, \quad k \notin N_s \cup N_t. \qquad \text{(I-2)}$$

Strong separability with respect to the partition R is necessary and sufficient for the production function $f(X)$ to be of the form $f(x^1 + x^2 + \ldots + x^r)$, where x^s is a function of the elements of N_s only.

Therefore, weak separability should be assumed to define a production function with a few inputs which are integrated among a

variety of inputs at least[9]. That is, weak separability among capital (K), labor (L), energy (E), and material (M) is indispensable in the KLEM model.

In application of the KLEM model, it is more general to analyze a cost function based on duality than a production function itself (Binswanger, 1974). If a production function satisfies weak separability and homotheticity, its dual cost function is also weakly separable and homothetic in input factors.

2. 2. Separability Test

Empirical method for testing separability was firstly suggested by Berndt and Christensen (1973, 1974). They proposed an alternative definition of separability that the Allen partial elasticities of substitution between factors in the separable group are equal for all factors. However, their contention was criticized because it assumes implicitly that a translog function represents exactly the underlying production process (Denny and Fuss, 1977; Jorgenson and Lau, 1975). Instead, Denny and Fuss (1977) developed tests based on a

[9] Both a Cobb-Douglas production function and a constant elasticity of substitution (CES) production function are realized on the premise of strong separability.

translog function as a quadratic approximation which is less restrictive than the method of Berndt and Christensen (1973, 1974). Denny and Fuss (1977)'s method has been widely applied in testing separability until these days (Serletis et al., 2010b). So, it is adopted in this thesis and introduced here.

Suppose a production technology containing inputs of x_1, x_2, and x_3. Let the true production function of this technology, which is weakly separable in x_1 and x_2 from x_3, be

$$\ln Y = f(\ln g(\ln x_1, \ln x_2), \ln x_3), \tag{I-3}$$

where Y is output, x_i $(i = 1,2,3)$ are inputs, and $g(\cdot)$ is an input aggregator function. If $f(\cdot)$ is approximated in a translog form, the approximated production function is given by

$$\ln Y = \ln \alpha_0 + \sum_{i=1}^{3} \beta_i \ln x_i + \frac{1}{2} \sum_{i=1}^{3} \sum_{j=1}^{3} \beta_{ij} \ln x_i \ln x_j . \tag{I-4}$$

The above translog function with symmetry ($\beta_{ij} = \beta_{ji}$) is a quadratic approximation around $\boldsymbol{x}^*$ to the true production function $f(\cdot)$. Then,

$$\beta_i = \frac{\partial f}{\partial g} \cdot \left. \frac{\partial g}{\partial \ln x} \right|_{x^*}, \quad i = 1,2 \tag{I-5}$$

$$\beta_{i3} = \beta_{3i} = \frac{\partial g}{\partial \ln x_i} \cdot \left. \frac{\partial^2 f}{\partial g \partial \ln x_3} \right|_{x^*}, \quad i = 1,2 \tag{I-6}$$

Thus, it can be seen that the above parameters satisfy the constraint

$$\frac{\beta_1}{\beta_2} = \left| \frac{\partial g}{\partial \ln x_1} \Big/ \frac{\partial g}{\partial \ln x_3} \right|_{x^*} = \frac{\beta_{13}}{\beta_{23}}. \tag{I-7}$$

The parameter constraint shown in Eq. (I-7) is consequent on the separability pattern shown in Eq. (I-3). The above discussion is also applicable the case of more than three inputs. By the duality theorem (Shephard, 1953), the same parameter constraint in Eq. (I-7) can be derived.

3. Framework for Testing Separability between Energy and Capital

To analyze separability between energy and capital, components of capital and energy aggregates should be firstly defined. Then, a translog cost function with those components is estimated[10]. Then, separability patterns are identified based on this identification of components. Using the parameter estimates of the translog function, test for the separability patterns is conducted. This chapter explains those procedures for testing separability between energy and capital.

3. 1. Components of Capital and Energy Aggregates

Classification of capital assets has been intensively discussed in the studies about assessment on capital stock. These studies have been interested in assigning depreciation rates to capital assets. It is really impossible to identify every depreciation rate. So, capital assets are classified into several types, and depreciation rates within the

[10] In case of including labor and material, it is hard to concentrate on the issue of separability between energy and capital. So, labor and material are not considered in Part I.

type are assumed to be identical (Pyo, 2003).

The academic discussions on the categorization of capital assets started from the benchmark study of Christensen and Jorgenson (1969). They addressed that capital aggregate consists of the seven assets, *i.e.*, consumer's durables, non-residential structures, producer's durables, residential structures, non-farm inventories, farm inventories, and land. On the other hand, Field and Grebenstein (1980) pointed out that various capital assets can be classified into physical capital and working capital. Physical capital refers to actual machinery while working capital does other types of capital, such as buildings and structures, land, and monetary assets. Similarly, Garofalo and Malhotra (1988) classified capital into machinery and buildings. In Korea, Pyo (2003) presented that various capital assets are categorized as residential buildings, non-residential buildings, structures, transport equipment, and machinery.

Also, some international organizations and economic institutions have classified the types of capital assets and provided related statistical data. SNA (1993) classified capital assets into machinery and equipment, buildings and structure, and other assets. OECD (2001) did capital assets into twelve types: dwellings; other machinery and buildings; major improvement of dwellings and other buildings and structures; transport equipment; other machinery and

equipment; cultivated assets; mineral exploration; computer software; entertainment, literary and artistic originals; and major improvements to tangible non-produced assets. The BEA (US Bureau of Economic Analysis) covers the data of capital assets and suggests a standard in defining capital assets. It defines components of capital aggregate as private non-residential equipment, non-residential structures, residential capital, durable goods owned by consumers, and government non-residential equipment (BEA, 2003). It also enumerates a detailed list of assets which belongs to these five sub-categories. Meanwhile, the EU KLEMS consortium (Timmer et al., 2007) suggested a minimum level of asset type detail was defined to which all of its member country adhere. It primarily defines components of capital aggregate as ICT (information and communication technology) assets, residential structures, non-residential structures, machinery and equipment, and transport equipment.

Headed by the classification of the EU KLEMS consortium, the ICT assets, once considered as a component of machinery, are treated like a separate group. The reason of this change is that the depreciation rates of the ICT assets are considerably greater than other assets belonging machinery. Besides, ICT assets are related with the brisk discussions on Solow (1987)’s paradox (Jorgenson and

Stiroh, 1999; Triplett, 1999).

This thesis conducts an in-depth test for separability between capital and energy within the manufacturing sector of the ten countries using the data provided by the EU KLEMS consortium. Therefore, components of capital aggregate (K) in this thesis are defined based on the discussion of the EU KLEMS consortium. The discussions of the literatures, the international organizations, and the economic institutions which have been mentioned above are also referred to. So, capital aggregate in this thesis consists of three asset types: ICT (information and communication technology) capital (K_I), machinery (K_M), and buildings (K_B) (See Table I-1).

Table I-1. List of Capital Asset Types

Capital asset	List
ICT assets (K_I)	Computing equipment
	Communication equipment
	Software
Machinery (K_M)	Transport equipment
	Other machinery and equipment
Buildings (K_B)	Total non-residential structures
	Residential structures

As components of energy aggregate (E), most of the studies have referred to four energy types: coal (E_C); oil (E_O); gas (E_G); and electricity (E_E) (Fuss, 1977; Harvey and Marshall, 1991; Serletis et

al., 2010b; Truong, 1985; Urga and Walters, 2003). Thus, this thesis defines components of energy aggregate identical with these studies[11].

3. 2. Approximation of Cost Function

This thesis applies the Denny and Fuss (1977)'s method to the case of a cost function. An arbitrary cost function with n inputs is defined as

$$\ln C = f(\ln p_{x_1}, \ldots, \ln p_{x_n}) \tag{I-8}$$

The approximation of this cost function by a translog form gives

$$\ln C = \alpha_0 + \sum_i \beta_i \ln p_i + \frac{1}{2} \sum_i \sum_j \beta_{ij} \ln p_i \ln p_j, \quad i, j = x_1, \ldots, x_n \tag{I-9}$$

[11] Unlike most of the studies, Considine (1989b) and Bjöner and Jensen (2002) defined components of an energy aggregate differently. They commonly focused on the final energy usages, *i.e.*, electricity and heat, because they tried to separate energy-material which is hard to be substituted. This thesis does not follow their approach since substitution of energy-material is not interested in.

Here, symmetry and homogeneity of degree one in prices[12] are imposed by

Symmetry: $\beta_{ij} = \beta_{ji}$

Homogeneity: $\sum_i \beta_i = 1, \ \sum_i \beta_{ij} = 0.$

In general, estimation of first derivatives of Eq. (I-9) is preferred than direct estimation of it because of co-linearity problem. By Shephard's lemma (Diewert, 1971), the system of cost shares associated with Eq. (I-9) is the logarithmic derivatives and is given by

$$S_i = \beta_i + \sum_j \beta_{ij} \ln p_j, \quad i, j = x_1, \ldots, x_n \tag{I-10}$$

If an arbitrary cost function is weakly separable in x_1 and x_2 from other factors, *i.e.*, $\ln C = f(\ln g(\ln p_{x_1}, \ln p_{x_2}), \ln p_{x_3} \ldots, \ln p_{x_n})$, then the parameter constraints consequent on this separability are

[12] Homogeneity of degree one in prices does not impose homogeneity of degree one of the production function in inputs.

$$\frac{\beta_1}{\beta_2} = \frac{\beta_{13}}{\beta_{23}} = \ldots = \frac{\beta_{1n}}{\beta_{2n}}. \qquad \text{(I-11)}$$

Parameter constraints are different by separability pattern. Thus, the separability pattern is considered *in prior* to derive parameter restriction for weak separability.

3. 3. Framework for Separability Test

Suppose a production technology of which the input factors are three types of capital assets and four energy sources. Then, three cases are assumed for separability test. The first case deals with whether energy aggregate (E) and capital aggregate (K) are weakly separable from each other. The second case refers to weak separability among three capital assets (K_I, K_M, K_B), assumed the existence of energy aggregate. The third case is weak separability among four energy sources (E_C, E_O, E_G, E_E), assumed the existence of capital aggregate.

(1) *Case 1*: Weak separability between capital and energy

To test whether energy aggregate E and capital aggregate (K)

are weakly separable from each other, a cost function which assumes three capital assets and four energy sources as input factors should be firstly defined as

$$\ln C = f(\ln p_{K_I}, \ln p_{K_M}, \ln p_{K_B}, \ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}) . \text{(I-12)}$$

If the above cost function is approximated by a translog function, the system of cost share equations shown in Eq. (I-13) is used for actual estimation.

$$\begin{aligned}
S_{K_I} &= \beta_{K_I} + \beta_{K_I K_I} \ln p_{K_I} + \beta_{K_I K_M} \ln p_{K_M} + \beta_{K_I K_B} \ln p_{K_B} \\
&\quad + \beta_{K_I E_C} \ln p_{E_C} + \beta_{K_I E_O} \ln p_{E_O} + \beta_{K_I E_G} \ln p_{E_G} + \beta_{K_I E_E} \ln p_{E_E} \\
S_{K_M} &= \beta_{K_M} + \beta_{K_I K_M} \ln p_{K_I} + \beta_{K_M K_M} \ln p_{K_M} + \beta_{K_M K_B} \ln p_{K_B} \\
&\quad + \beta_{K_M E_C} \ln p_{E_C} + \beta_{K_M E_O} \ln p_{E_O} + \beta_{K_M E_G} \ln p_{E_G} + \beta_{K_M E_E} \ln p_{E_E} \\
S_{K_B} &= \beta_{K_B} + \beta_{K_I K_B} \ln p_{K_I} + \beta_{K_M K_B} \ln p_{K_M} + \beta_{K_B K_B} \ln p_{K_B} \\
&\quad + \beta_{K_B E_C} \ln p_{E_C} + \beta_{K_B E_O} \ln p_{E_O} + \beta_{K_B E_G} \ln p_{E_G} + \beta_{K_B E_E} \ln p_{E_E} \\
S_{E_C} &= \beta_{E_C} + \beta_{K_I E_C} \ln p_{K_I} + \beta_{K_M E_C} \ln p_{K_M} + \beta_{K_B E_C} \ln p_{K_B} \\
&\quad + \beta_{E_C E_C} \ln p_{E_C} + \beta_{E_C E_O} \ln p_{E_O} + \beta_{E_C E_G} \ln p_{E_G} + \beta_{E_C E_E} \ln p_{E_E} \\
S_{E_O} &= \beta_{E_O} + \beta_{K_I E_O} \ln p_{K_I} + \beta_{K_M E_O} \ln p_{K_M} + \beta_{K_B E_O} \ln p_{K_B} \\
&\quad + \beta_{E_C E_O} \ln p_{E_C} + \beta_{E_O E_O} \ln p_{E_O} + \beta_{E_O E_G} \ln p_{E_G} + \beta_{E_O E_E} \ln p_{E_E} \\
S_{E_G} &= \beta_{E_G} + \beta_{K_I E_G} \ln p_{K_I} + \beta_{K_M E_G} \ln p_{K_M} + \beta_{K_B E_G} \ln p_{K_B} \\
&\quad + \beta_{E_C E_G} \ln p_{E_C} + \beta_{E_O E_G} \ln p_{E_O} + \beta_{E_G E_G} \ln p_{E_G} + \beta_{E_G E_E} \ln p_{E_E} \\
S_{E_E} &= \beta_{E_E} + \beta_{K_I E_E} \ln p_{K_I} + \beta_{K_M E_E} \ln p_{K_M} + \beta_{K_B E_E} \ln p_{K_B} \\
&\quad + \beta_{E_C E_E} \ln p_{E_C} + \beta_{E_O E_E} \ln p_{E_O} + \beta_{E_G E_E} \ln p_{E_G} + \beta_{E_E E_E} \ln p_{E_E}
\end{aligned} \quad \text{(I-13)}$$

Then, the separability pattern in the *Case 1* and its corresponding parameter restrictions are derived as Table I-2.

Table I-2. Separability Pattern and Restrictions: *Case 1*

Separability Pattern	Parameter restrictions
$f(g(\ln p_{K_I}, \ln p_{K_M}, \ln p_{K_B}), h(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}))$	$\frac{\beta_{K_I}}{\beta_{K_M}} = \frac{\beta_{K_I E_C}}{\beta_{K_M E_C}} = \frac{\beta_{K_I E_O}}{\beta_{K_M E_O}} = \frac{\beta_{K_I E_G}}{\beta_{K_M E_G}} = \frac{\beta_{K_I E_E}}{\beta_{K_M E_E}},$ $\frac{\beta_{K_I}}{\beta_{K_B}} = \frac{\beta_{K_I E_C}}{\beta_{K_B E_C}} = \frac{\beta_{K_I E_O}}{\beta_{K_B E_O}} = \frac{\beta_{K_I E_G}}{\beta_{K_B E_G}} = \frac{\beta_{K_I E_E}}{\beta_{K_B E_E}},$ $\frac{\beta_{E_C}}{\beta_{E_O}} = \frac{\beta_{K_I E_C}}{\beta_{K_I E_O}} = \frac{\beta_{K_M E_C}}{\beta_{K_M E_O}} = \frac{\beta_{K_B E_C}}{\beta_{K_B E_O}},$ $\frac{\beta_{E_C}}{\beta_{E_G}} = \frac{\beta_{K_I E_C}}{\beta_{K_I E_G}} = \frac{\beta_{K_M E_C}}{\beta_{K_M E_G}} = \frac{\beta_{K_B E_C}}{\beta_{K_B E_G}},$ $\frac{\beta_{E_C}}{\beta_{E_E}} = \frac{\beta_{K_I E_C}}{\beta_{K_I E_E}} = \frac{\beta_{K_M E_C}}{\beta_{K_M E_E}} = \frac{\beta_{K_B E_C}}{\beta_{K_B E_E}}$

[a] K_I: ICT assets, K_M: Machinery, K_B: Buildings; E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

If the parameter restrictions in Table I-2 are not rejected, capital aggregate and energy aggregate are weakly separable from each other. It means that the aggregation process of three capital assets is irrelevant of that of four energy sources, or vice versa. If not, capital aggregate energy aggregates are not weakly separable from each other. This result implies that the combination of three capital assets is actually relevant to that of four energy sources.

(2) *Case 2*: Weak separability among three capital assets

The second case refers to weak separability among three capital assets, assumed that the aggregation of energy sources is irrelevant to the capital assets. To test weak separability among three capital assets with energy aggregate, a cost function, which employs K_I, K_M, K_B, and E as input factors, is defined as

$$\ln C = f(\ln p_{K_I}, \ln p_{K_M}, \ln p_{K_B}, \ln p_E). \qquad \text{(I-14)}$$

If the above cost function is approximated by a translog function, the system of cost share equations shown in Eq. (I-15) is used for actual estimation.

$$
\begin{aligned}
S_{K_I} &= \beta_{K_I} + \beta_{K_I K_I} \ln p_{K_I} + \beta_{K_I K_M} \ln p_{K_M} \\
&\quad + \beta_{K_I K_B} \ln p_{K_B} + \beta_{K_I E} \ln p_E \\
S_{K_M} &= \beta_{K_M} + \beta_{K_I K_M} \ln p_{K_I} + \beta_{K_M K_M} \ln p_{K_M} \\
&\quad + \beta_{K_M K_B} \ln p_{K_B} + \beta_{K_M E} \ln p_E \\
S_{K_B} &= \beta_{K_B} + \beta_{K_I K_B} \ln p_{K_I} + \beta_{K_M K_B} \ln p_{K_M} \\
&\quad + \beta_{K_B K_B} \ln p_{K_B} + \beta_{K_B E} \ln p_E \\
S_E &= \beta_E + \beta_{K_I E} \ln p_{K_I} + \beta_{K_M E} \ln p_{K_M} \\
&\quad + \beta_{K_B M} \ln p_{K_B} + \beta_{EE} \ln p_E
\end{aligned}
\qquad \text{(I-15)}
$$

In the *Case 2*, four separability patterns are identified. The patterns and their corresponding parametric restrictions are shown in Table I-3. The *Case 2* analyzes the possibility of aggregation among capital assets. If any of the parameter restrictions is not rejected, two or three capital assets can be consistently aggregated.

Table I-3. Separability Patterns and Restrictions: *Case 2*

Separability Pattern	Parametric Restrictions
$f(g(\ln p_{K_I}, \ln p_{K_M}, \ln p_{K_B}), \ln p_E)$	$\frac{\beta_{K_I}}{\beta_{K_M}} = \frac{\beta_{K_I E}}{\beta_{K_M E}}, \ \frac{\beta_{K_I}}{\beta_{K_B}} = \frac{\beta_{K_I E}}{\beta_{K_B E}}$
$f(g(\ln p_{K_I}, \ln p_{K_M}), \ln p_{K_B}, \ln p_E)$	$\frac{\beta_{K_I}}{\beta_{K_M}} = \frac{\beta_{K_I K_B}}{\beta_{K_M K_B}} = \frac{\beta_{K_I E}}{\beta_{K_M E}}$
$f(g(\ln p_{K_I}, \ln p_{K_B}), \ln p_{K_M}, \ln p_E)$	$\frac{\beta_{K_I}}{\beta_{K_B}} = \frac{\beta_{K_I K_M}}{\beta_{K_M K_B}} = \frac{\beta_{K_I E}}{\beta_{K_B E}}$
$f(g(\ln p_{K_M}, \ln p_{K_B}), \ln p_{K_I}, \ln p_E)$	$\frac{\beta_{K_M}}{\beta_{K_B}} = \frac{\beta_{K_I K_M}}{\beta_{K_I K_B}} = \frac{\beta_{K_M E}}{\beta_{K_B E}}$

[a] K_I: ICT assets, K_M: Machinery, K_B: Buildings; E: Energy aggregate

(3) *Case 3*: Weak separability among four energy sources

The third case deals with separability among four energy sources, assumed that the aggregation process of capital assets is irrelevant to the energy sources. To test weak separability among four energy sources with capital aggregate, a cost function, which employs E_C, E_O, E_G, E_E and K as input factors, is defined as

$$\ln C = f(\ln p_K, \ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}). \qquad \text{(I-16)}$$

If the above cost function is approximated by a translog function, the system of cost share equations shown in Eq. (I-17) is used for actual estimation.

$$
\begin{aligned}
S_K &= \beta_K + \beta_{KK} \ln p_K + \beta_{KE_C} \ln p_{E_C} + \beta_{KE_O} \ln p_{E_O} \\
&\quad + \beta_{KE_G} \ln p_{E_G} + \beta_{KE_E} \ln p_{E_E} \\
S_{E_C} &= \beta_{E_C} + \beta_{KE_C} \ln p_K + \beta_{E_CE_C} \ln p_{E_C} + \beta_{E_CE_O} \ln p_{E_O} \\
&\quad + \beta_{E_CE_G} \ln p_{E_G} + \beta_{E_CE_E} \ln p_{E_E} \\
S_{E_O} &= \beta_{E_O} + \beta_{KE_O} \ln p_K + \beta_{E_CE_O} \ln p_{E_C} + \beta_{E_OE_O} \ln p_{E_O} \\
&\quad + \beta_{E_OE_G} \ln p_{E_G} + \beta_{E_OE_E} \ln p_{E_E} \\
S_{E_G} &= \beta_{E_G} + \beta_{KE_G} \ln p_K + \beta_{E_CE_G} \ln p_{E_C} + \beta_{E_OE_G} \ln p_{E_O} \\
&\quad + \beta_{E_GE_G} \ln p_{E_G} + \beta_{E_GE_E} \ln p_{E_E} \\
S_{E_E} &= \beta_{E_E} + \beta_{KE_E} \ln p_K + \beta_{E_CE_E} \ln p_{E_C} + \beta_{E_OE_E} \ln p_{E_O} \\
&\quad + \beta_{E_GE_E} \ln p_{E_G} + \beta_{E_EE_E} \ln p_{E_E}
\end{aligned}
\qquad \text{(I-17)}
$$

In the *Case 3*, eleven types of separability patterns are identified. These separability patterns and their corresponding parametric restrictions are shown in Table I-4. The *Case 3* analyzes the possibility of aggregation among energy sources. If any of the parameter restrictions is not rejected, two or three or four energy sources can be consistently aggregated.

Table I-4. Separability Patterns and Restrictions: *Case 3*

Separability Pattern	Parametric Restrictions
$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}))$	$\frac{\beta_{E_C}}{\beta_{E_O}} = \frac{\beta_{KE_C}}{\beta_{KE_O}}$, $\frac{\beta_{E_C}}{\beta_{E_G}} = \frac{\beta_{KE_C}}{\beta_{KE_G}}$, $\frac{\beta_{E_C}}{\beta_{E_E}} = \frac{\beta_{KE_C}}{\beta_{KE_E}}$
$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}), \ln p_{E_E})$	$\frac{\beta_{E_C}}{\beta_{E_O}} = \frac{\beta_{KE_C}}{\beta_{KE_O}} = \frac{\beta_{E_CE_E}}{\beta_{E_OE_E}}$, $\frac{\beta_{E_C}}{\beta_{E_G}} = \frac{\beta_{KE_C}}{\beta_{KE_G}} = \frac{\beta_{E_CE_E}}{\beta_{E_GE_E}}$
$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_E}), \ln p_{E_G})$	$\frac{\beta_{E_C}}{\beta_{E_O}} = \frac{\beta_{KE_C}}{\beta_{KE_O}} = \frac{\beta_{E_CE_G}}{\beta_{E_OE_G}}$, $\frac{\beta_{E_C}}{\beta_{E_E}} = \frac{\beta_{KE_C}}{\beta_{KE_E}} = \frac{\beta_{E_CE_G}}{\beta_{E_GE_E}}$
$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_G}, \ln p_{E_E}), \ln p_{E_O})$	$\frac{\beta_{E_C}}{\beta_{E_G}} = \frac{\beta_{KE_C}}{\beta_{KE_G}} = \frac{\beta_{E_CE_O}}{\beta_{E_OE_G}}$, $\frac{\beta_{E_C}}{\beta_{E_E}} = \frac{\beta_{KE_C}}{\beta_{KE_E}} = \frac{\beta_{E_1E_2}}{\beta_{E_2E_4}}$
$f(\ln p_K, g(\ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}), \ln p_{E_C})$	$\frac{\beta_{E_O}}{\beta_{E_G}} = \frac{\beta_{KE_O}}{\beta_{KE_G}} = \frac{\beta_{E_CE_O}}{\beta_{E_CE_G}}$, $\frac{\beta_{E_O}}{\beta_{E_E}} = \frac{\beta_{KE_O}}{\beta_{KE_E}} = \frac{\beta_{E_CE_O}}{\beta_{E_CE_E}}$

[a] K: Capital aggregate; E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table I-4. Separability Patterns and Restrictions: *Case 3* (Continued)

Separability Pattern	Parametric Restrictions
$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}), \ln p_{E_G}, \ln p_{E_E})$	$\frac{\beta_{E_C}}{\beta_{E_O}} = \frac{\beta_{KE_C}}{\beta_{KE_O}} = \frac{\beta_{E_CE_G}}{\beta_{E_OE_G}} = \frac{\beta_{E_CE_E}}{\beta_{E_OE_E}}$
$f(\ln p_K, \ln p_{E_C}, \ln p_{E_O}, g(\ln p_{E_G}, \ln p_{E_E}))$	$\frac{\beta_{E_G}}{\beta_{E_E}} = \frac{\beta_{KE_G}}{\beta_{KE_E}} = \frac{\beta_{E_CE_G}}{\beta_{E_CE_E}} = \frac{\beta_{E_OE_G}}{\beta_{E_OE_E}}$
$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_G}), \ln p_{E_O}, \ln p_{E_E})$	$\frac{\beta_{E_C}}{\beta_{E_G}} = \frac{\beta_{KE_C}}{\beta_{KE_G}} = \frac{\beta_{E_CE_O}}{\beta_{E_OE_G}} = \frac{\beta_{E_CE_E}}{\beta_{E_GE_E}}$
$f(\ln p_K, \ln p_{E_C}, \ln p_{E_G}, g(\ln p_{E_O}, \ln p_{E_E}))$	$\frac{\beta_{E_O}}{\beta_{E_E}} = \frac{\beta_{KE_O}}{\beta_{KE_E}} = \frac{\beta_{E_CE_O}}{\beta_{E_CE_E}} = \frac{\beta_{E_OE_G}}{\beta_{E_GE_E}}$
$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_E}), \ln p_{E_O}, \ln p_{E_G})$	$\frac{\beta_{E_C}}{\beta_{E_E}} = \frac{\beta_{KE_C}}{\beta_{KE_E}} = \frac{\beta_{E_CE_O}}{\beta_{E_OE_E}} = \frac{\beta_{E_CE_G}}{\beta_{E_GE_E}}$
$f(\ln p_K, \ln p_{E_C}, \ln p_{E_E}, g(\ln p_{E_O}, \ln p_{E_G}))$	$\frac{\beta_{E_O}}{\beta_{E_G}} = \frac{\beta_{KE_O}}{\beta_{KE_G}} = \frac{\beta_{E_CE_O}}{\beta_{E_CE_G}} = \frac{\beta_{E_OE_E}}{\beta_{E_GE_E}}$

[a] K: Capital aggregate; E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

4. Data

To conduct the separability test described in the Section 3, data of costs and prices for three capital assets and four energy sources in the manufacturing sector of the ten OECD countries are needed. The countries are Australia, Austria, Denmark, Finland, Japan, Korea, Netherlands, UK and US.

Data of three capital assets, *i.e.*, ICT capital (K_I), machinery (K_M), and buildings (K_B), are gathered from the EU KLEMS consortium. The consortium provides investment costs and stocks for these capital assets in the local currency. In specific, the 'capital compensation' and the 'real fixed capital stock in 1995 prices' is respectively regarded as the investment cost and the capital stock. Division of investment cost by its capital stock is considered as a price of the capital asset.

Data of four energy sources, *i.e.*, coal (E_C), oil (E_O), gas (E_G), and electricity (E_E), are gathered from the *Energy Prices and Taxes* series published by the IEA (International Energy Agency) (IEA, 2012), the *Energy Balances of OECD Countries* series also published by the IEA (IEA, 2011), and the EU KLEMS consortium. The *Energy Prices and Taxes* series provides the time series of price indices of four energy sources (p_{E_i}, $i = C, O, G, E$). The *Energy Balances of*

OECD Countries series gives the time series of consumptions for those energy sources (x_{E_i} , $i = C, O, G, E$). And, the EU KLEMS consortium gives the total energy cost of the manufacturing sector. Combining these data, cost shares for coal, oil, gas, and electricity (S_{E_i} , $i = C, O, G, E$) are derived.

Sample period is slightly different by country because of data availability and differences in the adoption of gas. For Australia, Austria, Finland, Italy, Netherlands, UK, and US, the sample period is from 1980 to 2007 ($T = 28$), for Denmark from 1984 to 2007 ($T = 24$), for Japan from 1980 to 2006 ($T = 27$), and for Korea from 1985 to 2007 ($T = 23$). All price data are normalized based on 1990=1. Sample mean and standard deviation of cost shares and prices are presented in Table I-5 and Table I-6, respectively.

Data of capital aggregate (K) and energy aggregate (E) are prepared based on the following rules. First, the cost share is the aggregation over cost shares for its components. Second, the price is derived by using the Divisia index. The Divisia index is obtained by cumulating the rate of the change to the values of an index of price change and is one of the exact and superlative index (Diewert, 1976). TSP 5.1 package provides a module for computing the Divisia price index by the command 'DIVIND' (Hall and Cummins, 2009).

Table I-5 describes sample mean cost shares for the three capital assets and four energy sources. Table I-6 describes sample prices of the three capital assets and four energy sources. All prices are normalized based on 1990=1.

Table I-5. Sample Mean Cost shares for Components of Capital and Energy Aggregates

	Capital			Energy			
	ICT assets (K_I)	Machinery (K_M)	Buildings (K_B)	Coal (E_C)	Oil (E_O)	Gas (E_G)	Electricity (E_E)
Australia	0.060 (0.017)	0.394 (0.045)	0.177 (0.040)	0.018 (0.008)	0.065 (0.048)	0.073 (0.015)	0.212 (0.039)
Austria	0.039 (0.015)	0.463 (0.038)	0.247 (0.036)	0.013 (0.009)	0.018 (0.013)	0.045 (0.012)	0.176 (0.050)
Denmark	0.101 (0.020)	0.406 (0.039)	0.206 (0.025)	0.012 (0.007)	0.060 (0.056)	0.071 (0.026)	0.144 (0.023)
Finland	0.062 (0.023)	0.414 (0.083)	0.216 (0.050)	0.035 (0.018)	0.091 (0.072)	0.031 (0.014)	0.133 (0.044)
Italy	0.050 (0.014)	0.489 (0.058)	0.175 (0.042)	0.005 (0.003)	0.070 (0.055)	0.026 (0.003)	0.184 (0.043)
Japan	0.049 (0.018)	0.412 (0.025)	0.325 (0.022)	0.009 (0.002)	0.038 (0.015)	0.007 (0.002)	0.160 (0.024)
Korea	0.028 (0.008)	0.391 (0.058)	0.111 (0.034)	0.008 (0.001)	0.154 (0.028)	0.015 (0.017)	0.294 (0.030)
Netherlands	0.057 (0.016)	0.335 (0.058)	0.182 (0.032)	0.009 (0.005)	0.049 (0.030)	0.129 (0.032)	0.239 (0.040)
UK	0.073 (0.035)	0.345 (0.063)	0.144 (0.037)	0.032 (0.024)	0.069 (0.029)	0.103 (0.027)	0.236 (0.028)
US	0.083 (0.347)	0.347 (0.046)	0.196 (0.039)	0.014 (0.009)	0.061 (0.062)	0.115 (0.039)	0.184 (0.043)

[a] Standard deviations are presented in the parenthesis.

Table I-6. Sample Mean Price indices of Components of Capital and Energy Aggregates (1990=1)

	Capital			Energy			
	ICT assets (K_I)	Machinery (K_M)	Buildings (K_B)	Coal (E_C)	Oil (E_O)	Gas (E_G)	Electricity (E_E)
Australia	0.761 (0.249)	1.153 (0.390)	1.090 (0.437)	1.777 (0.827)	1.743 (0.473)	1.732 (0.686)	1.607 (0.576)
Austria	0.890 (0.333)	1.322 (0.655)	1.273 (0.674)	0.870 (0.010)	0.924 (0.162)	0.942 (0.139)	0.831 (0.086)
Denmark	0.766 (0.439)	1.222 (0.238)	1.405 (0.281)	1.234 (0.571)	1.260 (0.705)	1.100 (0.288)	1.308 (0.421)
Finland	1.042 (0.143)	1.447 (0.626)	1.511 (0.756)	1.788 (0.829)	2.040 (1.228)	1.921 (0.792)	1.682 (0.794)
Italy	0.943 (0.115)	1.054 (0.250)	1.404 (0.514)	1.485 (0.591)	1.649 (0.768)	1.561 (0.685)	1.320 (0.415)
Japan	0.922 (0.407)	0.815 (0.184)	0.804 (0.142)	1.015 (0.225)	1.243 (0.465)	1.038 (0.108)	1.041 (0.143)
Korea	1.147 (0.391)	1.317 (0.306)	3.735 (1.742)	1.670 (0.732)	3.384 (2.463)	3.176 (2.404)	1.642 (0.430)
Netherlands	0.901 (0.162)	1.081 (0.293)	1.135 (0.464)	1.203 (0.396)	1.171 (0.410)	1.401 (0.619)	1.359 (0.465)
UK	0.974 (0.175)	0.944 (0.321)	0.862 (0.292)	1.096 (0.320)	1.687 (0.672)	1.439 (0.625)	1.269 (0.278)
US	0.850 (0.200)	1.086 (0.331)	1.083 (0.450)	0.861 (0.155)	1.062 (0.527)	1.257 (0.676)	0.850 (0.151)

[a] Standard deviations are presented in the parenthesis.

5. Test Results

Test results of the parameter restrictions corresponding to the sixteen separability patterns are demonstrated in Table I-7 to I-16 by country. Parameter estimates of the translog function shown in Eq. (I-13), Eq. (I-15) and Eq. (I-17), which are the basis of the separability test, are presented in the Appendix I. The Wald statistics is used for the test.

The *Case 1* analyzes weak separability between energy aggregate and capital aggregate. In every country analyzed, the null hypothesis that theses aggregates are weakly separable from each other is rejected at the 1% significance level. This result reveals that the assumption of separability between energy and capital is not theoretically permissible. This interpretation is generally applicable because all the test results indicate same implication in the ten countries. Therefore, what type of capital asset is invested has an influence on the energy mix. This result refute the Fuss (1977)'s contention. Eventually, this result shows that division of capital and energy into sub-inputs is needed to measure substitutability between energy and capital sophisticatedly.

The *Case 2* tests the null hypotheses on whether any combination of three capital assets, *i.e.*, ICT assets (K_I), machinery (K_M), and

buildings (K_B), is weakly separable from the other capital asset and energy aggregate. For the relevant four separability patterns, all the null hypotheses are rejected at the 5% significance level in every country analyzed. Namely, any combination of three capital assets are not weakly separable from each other as well as energy aggregate. By these test results, it is likely that any aggregate among three capital assets is may not be consistently derived.

The *Case 3* tests the null hypotheses on whether any combination of four energy sources, *i.e.*, coal (E_C), oil (E_O), gas (E_G), and electricity (E_E), is weakly separable from the other energy sources and capital aggregate. For the relevant eleven separability patterns, all the null hypotheses are rejected at the 1% significance level in Australia, Denmark, Finland, Japan, Netherlands, UK, and US. This result demonstrates that in these countries, any combination of four energy sources are not weakly separable from each other as well as capital aggregate. In Austria, coal and oil are weakly separable from gas, electricity, and capital aggregate. In Italy, coal, oil, and gas are weakly separable from electricity and capital aggregate, and gas and electricity are weakly separable from coal, oil, and capital aggregate. Atypically, four energy sources are weakly separable from capital aggregate in Korea. That is, the only country where energy sources are consistently aggregated is Korea. Combining the results analyzing

the Case 3, it is likely that the energy aggregate consisting of four energy sources is not consistently derived, except Korea.

Table I-7. Test Results of Separability (Australia)

Case	Separability Pattern	χ^2	*p*-value
Case 1	$f(g(\ln p_{K_I}, \ln p_{K_M}, \ln p_{K_B}), h(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}))$	817349.31	(0.000)
Case 2	$f(g(\ln p_{K_I}, \ln p_{K_M}, \ln p_{K_B}), \ln p_E)$	78.92	(0.000)
	$f(g(\ln p_{K_I}, \ln p_{K_M}), \ln p_{K_B}, \ln p_E)$	59.01	(0.000)
	$f(g(\ln p_{K_I}, \ln p_{K_B}), \ln p_{K_M}, \ln p_E)$	46.72	(0.000)
	$f(g(\ln p_{K_M}, \ln p_{K_B}), \ln p_{K_I}, \ln p_E)$	12.86	(0.002)
Case 3	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}))$	14.31	(0.003)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}), \ln p_{E_E})$	242.47	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_E}), \ln p_{E_G})$	75.53	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_G}, \ln p_{E_E}), \ln p_{E_O})$	36.42	(0.000)
	$f(\ln p_K, g(\ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}), \ln p_{E_C})$	44.76	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}), \ln p_{E_G}, \ln p_{E_E})$	52.57	(0.000)
	$f(\ln p_K, \ln p_{E_C}, \ln p_{E_O}, g(\ln p_{E_G}, \ln p_{E_E}))$	527.45	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_G}), \ln p_{E_O}, \ln p_{E_E})$	29.30	(0.000)
	$f(\ln p_K, \ln p_{E_C}, \ln p_{E_G}, g(\ln p_{E_O}, \ln p_{E_E}))$	17.24	(0.001)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_E}), \ln p_{E_O}, \ln p_{E_G})$	63.56	(0.000)
	$f(\ln p_K, \ln p_{E_C}, \ln p_{E_E}, g(\ln p_{E_O}, \ln p_{E_G}))$	659.32	(0.000)

Table I-8. Test Results of Separability (Austria)

Case	Separability Pattern	χ^2	*p*-value
Case 1	$f(g(\ln p_{K_I}, \ln p_{K_M}, \ln p_{K_B}), h(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}))$	159316.53	(0.000)
Case 2	$f(g(\ln p_{K_I}, \ln p_{K_M}, \ln p_{K_B}), \ln p_E)$	6.89	(0.032)
	$f(g(\ln p_{K_I}, \ln p_{K_M}), \ln p_{K_B}, \ln p_E)$	485.91	(0.000)
	$f(g(\ln p_{K_I}, \ln p_{K_B}), \ln p_{K_M}, \ln p_E)$	189.37	(0.000)
	$f(g(\ln p_{K_M}, \ln p_{K_B}), \ln p_{K_I}, \ln p_E)$	18.99	(0.000)
Case 3	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}))$	70.05	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}), \ln p_{E_E})$	208.86	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_E}), \ln p_{E_G})$	82.79	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_G}, \ln p_{E_E}), \ln p_{E_O})$	145.42	(0.000)
	$f(\ln p_K, g(\ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}), \ln p_{E_C})$	194.84	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}), \ln p_{E_G}, \ln p_{E_E})$	4.72	(0.193)
	$f(\ln p_K, \ln p_{E_C}, \ln p_{E_O}, g(\ln p_{E_G}, \ln p_{E_E}))$	36.43	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_G}), \ln p_{E_O}, \ln p_{E_E})$	111.26	(0.000)
	$f(\ln p_K, \ln p_{E_C}, \ln p_{E_G}, g(\ln p_{E_O}, \ln p_{E_E}))$	164.93	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_E}), \ln p_{E_O}, \ln p_{E_G})$	43.61	(0.000)
	$f(\ln p_K, \ln p_{E_C}, \ln p_{E_E}, g(\ln p_{E_O}, \ln p_{E_G}))$	98.82	(0.000)

Table I-9. Test Results of Separability (Denmark)

Case	Separability Pattern	χ^2	*p*-value
Case 1	$f(g(\ln p_{K_I}, \ln p_{K_M}, \ln p_{K_B}), h(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}))$	$7.90*10^{10}$	(0.000)
Case 2	$f(g(\ln p_{K_I}, \ln p_{K_M}, \ln p_{K_B}), \ln p_E)$	1457.92	(0.000)
	$f(g(\ln p_{K_I}, \ln p_{K_M}), \ln p_{K_B}, \ln p_E)$	2014.23	(0.000)
	$f(g(\ln p_{K_I}, \ln p_{K_B}), \ln p_{K_M}, \ln p_E)$	1418.30	(0.000)
	$f(g(\ln p_{K_M}, \ln p_{K_B}), \ln p_{K_I}, \ln p_E)$	36.45	(0.000)
Case 3	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}))$	62.87	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}), \ln p_{E_E})$	20.49	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_E}), \ln p_{E_G})$	66.10	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_G}, \ln p_{E_E}), \ln p_{E_O})$	54.42	(0.000)
	$f(\ln p_K, g(\ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}), \ln p_{E_C})$	146.15	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}), \ln p_{E_G}, \ln p_{E_E})$	24.43	(0.000)
	$f(\ln p_K, \ln p_{E_C}, \ln p_{E_O}, g(\ln p_{E_G}, \ln p_{E_E}))$	80.28	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_G}), \ln p_{E_O}, \ln p_{E_E})$	18.21	(0.000)
	$f(\ln p_K, \ln p_{E_C}, \ln p_{E_G}, g(\ln p_{E_O}, \ln p_{E_E}))$	128.10	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_E}), \ln p_{E_O}, \ln p_{E_G})$	29.65	(0.000)
	$f(\ln p_K, \ln p_{E_C}, \ln p_{E_E}, g(\ln p_{E_O}, \ln p_{E_G}))$	16.04	(0.001)

Table I-10. Test Results of Separability (Finland)

Case	Separability Pattern	χ^2	*p*-value
Case 1	$f(g(\ln p_{K_I}, \ln p_{K_M}, \ln p_{K_B}), h(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}))$	49796.08	(0.000)
Case 2	$f(g(\ln p_{K_I}, \ln p_{K_M}, \ln p_{K_B}), \ln p_E)$	1110.55	(0.000)
	$f(g(\ln p_{K_I}, \ln p_{K_M}), \ln p_{K_B}, \ln p_E)$	269.36	(0.000)
	$f(g(\ln p_{K_I}, \ln p_{K_B}), \ln p_{K_M}, \ln p_E)$	66.13	(0.000)
	$f(g(\ln p_{K_M}, \ln p_{K_B}), \ln p_{K_I}, \ln p_E)$	437.34	(0.000)
Case 3	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}))$	64.39	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}), \ln p_{E_E})$	40.34	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_E}), \ln p_{E_G})$	50.79	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_G}, \ln p_{E_E}), \ln p_{E_O})$	95.32	(0.000)
	$f(\ln p_K, g(\ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}), \ln p_{E_C})$	58.06	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}), \ln p_{E_G}, \ln p_{E_E})$	42.02	(0.000)
	$f(\ln p_K, \ln p_{E_C}, \ln p_{E_O}, g(\ln p_{E_G}, \ln p_{E_E}))$	447.22	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_G}), \ln p_{E_O}, \ln p_{E_E})$	72.75	(0.000)
	$f(\ln p_K, \ln p_{E_C}, \ln p_{E_G}, g(\ln p_{E_O}, \ln p_{E_E}))$	64.07	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_E}), \ln p_{E_O}, \ln p_{E_G})$	48.84	(0.000)
	$f(\ln p_K, \ln p_{E_C}, \ln p_{E_E}, g(\ln p_{E_O}, \ln p_{E_G}))$	33.10	(0.000)

Table I-11. Test Results of Separability (Italy)

Case	Separability Pattern	χ^2	*p*-value
Case 1	$f(g(\ln p_{K_I}, \ln p_{K_M}, \ln p_{K_B}), h(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}))$	197265.76	(0.000)
Case 2	$f(g(\ln p_{K_I}, \ln p_{K_M}, \ln p_{K_B}), \ln p_E)$	3096.81	(0.000)
	$f(g(\ln p_{K_I}, \ln p_{K_M}), \ln p_{K_B}, \ln p_E)$	67.69	(0.000)
	$f(g(\ln p_{K_I}, \ln p_{K_B}), \ln p_{K_M}, \ln p_E)$	1958.87	(0.000)
	$f(g(\ln p_{K_M}, \ln p_{K_B}), \ln p_{K_I}, \ln p_E)$	2828.61	(0.000)
Case 3	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}))$	8.58	(0.035)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}), \ln p_{E_E})$	489.79	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_E}), \ln p_{E_G})$	6.67	(0.154)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_G}, \ln p_{E_E}), \ln p_{E_O})$	49.57	(0.000)
	$f(\ln p_K, g(\ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}), \ln p_{E_C})$	19.79	(0.001)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}), \ln p_{E_G}, \ln p_{E_E})$	811.98	(0.000)
	$f(\ln p_K, \ln p_{E_C}, \ln p_{E_O}, g(\ln p_{E_G}, \ln p_{E_E}))$	5.62	(0.131)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_G}), \ln p_{E_O}, \ln p_{E_E})$	10.48	(0.015)
	$f(\ln p_K, \ln p_{E_C}, \ln p_{E_G}, g(\ln p_{E_O}, \ln p_{E_E}))$	45.94	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_E}), \ln p_{E_O}, \ln p_{E_G})$	18.12	(0.000)
	$f(\ln p_K, \ln p_{E_C}, \ln p_{E_E}, g(\ln p_{E_O}, \ln p_{E_G}))$	327.55	(0.000)

Table I-12. Test Results of Separability (Japan)

Case	Separability Pattern	χ^2	*p*-value
Case 1	$f(g(\ln p_{K_I}, \ln p_{K_M}, \ln p_{K_B}), h(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}))$	$7.27*10^6$	(0.000)
Case 2	$f(g(\ln p_{K_I}, \ln p_{K_M}, \ln p_{K_B}), \ln p_E)$	4243.68	(0.000)
	$f(g(\ln p_{K_I}, \ln p_{K_M}), \ln p_{K_B}, \ln p_E)$	1420.57	(0.000)
	$f(g(\ln p_{K_I}, \ln p_{K_B}), \ln p_{K_M}, \ln p_E)$	5483.17	(0.000)
	$f(g(\ln p_{K_M}, \ln p_{K_B}), \ln p_{K_I}, \ln p_E)$	2943.57	(0.000)
Case 3	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}))$	61.45	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}), \ln p_{E_E})$	57.51	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_E}), \ln p_{E_G})$	389.59	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_G}, \ln p_{E_E}), \ln p_{E_O})$	489.64	(0.000)
	$f(\ln p_K, g(\ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}), \ln p_{E_C})$	185.87	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}), \ln p_{E_G}, \ln p_{E_E})$	14.49	(0.002)
	$f(\ln p_K, \ln p_{E_C}, \ln p_{E_O}, g(\ln p_{E_G}, \ln p_{E_E}))$	343.75	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_G}), \ln p_{E_O}, \ln p_{E_E})$	21.73	(0.000)
	$f(\ln p_K, \ln p_{E_C}, \ln p_{E_G}, g(\ln p_{E_O}, \ln p_{E_E}))$	198.23	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_E}), \ln p_{E_O}, \ln p_{E_G})$	293.43	(0.000)
	$f(\ln p_K, \ln p_{E_C}, \ln p_{E_E}, g(\ln p_{E_O}, \ln p_{E_G}))$	44.51	(0.000)

Table I-13. Test Results of Separability (Korea)

Case	Separability Pattern	χ^2	*p*-value
Case 1	$f(g(\ln p_{K_I}, \ln p_{K_M}, \ln p_{K_B}), h(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}))$	$4.54*10^{14}$	(0.000)
Case 2	$f(g(\ln p_{K_I}, \ln p_{K_M}, \ln p_{K_B}), \ln p_E)$	45.31	(0.000)
	$f(g(\ln p_{K_I}, \ln p_{K_M}), \ln p_{K_B}, \ln p_E)$	32.82	(0.000)
	$f(g(\ln p_{K_I}, \ln p_{K_B}), \ln p_{K_M}, \ln p_E)$	69.55	(0.000)
	$f(g(\ln p_{K_M}, \ln p_{K_B}), \ln p_{K_I}, \ln p_E)$	61.20	(0.000)
Case 3	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}))$	5.658	(0.130)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}), \ln p_{E_E})$	6.014	(0.198)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_E}), \ln p_{E_G})$	5.72	(0.221)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_G}, \ln p_{E_E}), \ln p_{E_O})$	6.623	(0.157)
	$f(\ln p_K, g(\ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}), \ln p_{E_C})$	343.97	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}), \ln p_{E_G}, \ln p_{E_E})$	1.58	(0.664)
	$f(\ln p_K, \ln p_{E_C}, \ln p_{E_O}, g(\ln p_{E_G}, \ln p_{E_E}))$	92.33	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_G}), \ln p_{E_O}, \ln p_{E_E})$	1.88	(0.597)
	$f(\ln p_K, \ln p_{E_C}, \ln p_{E_G}, g(\ln p_{E_O}, \ln p_{E_E}))$	127.08	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_E}), \ln p_{E_O}, \ln p_{E_G})$	19.97	(0.000)
	$f(\ln p_K, \ln p_{E_C}, \ln p_{E_E}, g(\ln p_{E_O}, \ln p_{E_G}))$	5.66	(0.130)

Table I-14. Test Results of Separability (Netherlands)

Case	Separability Pattern	χ^2	*p*-value
Case 1	$f(g(\ln p_{K_I}, \ln p_{K_M}, \ln p_{K_B}), h(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}))$	96612.87	(0.000)
Case 2	$f(g(\ln p_{K_I}, \ln p_{K_M}, \ln p_{K_B}), \ln p_E)$	251.44	(0.000)
	$f(g(\ln p_{K_I}, \ln p_{K_M}), \ln p_{K_B}, \ln p_E)$	49.68	(0.000)
	$f(g(\ln p_{K_I}, \ln p_{K_B}), \ln p_{K_M}, \ln p_E)$	2489.71	(0.000)
	$f(g(\ln p_{K_M}, \ln p_{K_B}), \ln p_{K_I}, \ln p_E)$	1068.83	(0.000)
Case 3	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}))$	94.31	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}), \ln p_{E_E})$	227.64	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_E}), \ln p_{E_G})$	66.13	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_G}, \ln p_{E_E}), \ln p_{E_O})$	106.67	(0.000)
	$f(\ln p_K, g(\ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}), \ln p_{E_C})$	80.85	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}), \ln p_{E_G}, \ln p_{E_E})$	105.33	(0.000)
	$f(\ln p_K, \ln p_{E_C}, \ln p_{E_O}, g(\ln p_{E_G}, \ln p_{E_E}))$	204.56	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_G}), \ln p_{E_O}, \ln p_{E_E})$	144.20	(0.000)
	$f(\ln p_K, \ln p_{E_C}, \ln p_{E_G}, g(\ln p_{E_O}, \ln p_{E_E}))$	158.80	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_E}), \ln p_{E_O}, \ln p_{E_G})$	40.31	(0.000)
	$f(\ln p_K, \ln p_{E_C}, \ln p_{E_E}, g(\ln p_{E_O}, \ln p_{E_G}))$	141.22	(0.000)

Table I-15. Test Results of Separability (UK)

Case	Separability Pattern	χ^2	*p*-value
Case 1	$f(g(\ln p_{K_I}, \ln p_{K_M}, \ln p_{K_B}), h(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}))$	$7.43*10^7$	(0.000)
Case 2	$f(g(\ln p_{K_I}, \ln p_{K_M}, \ln p_{K_B}), \ln p_E)$	193.45	(0.000)
	$f(g(\ln p_{K_I}, \ln p_{K_M}), \ln p_{K_B}, \ln p_E)$	129.79	(0.000)
	$f(g(\ln p_{K_I}, \ln p_{K_B}), \ln p_{K_M}, \ln p_E)$	234.24	(0.000)
	$f(g(\ln p_{K_M}, \ln p_{K_B}), \ln p_{K_I}, \ln p_E)$	97.47	(0.000)
Case 3	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}))$	120.63	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}), \ln p_{E_E})$	355.01	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_E}), \ln p_{E_G})$	71.04	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_G}, \ln p_{E_E}), \ln p_{E_O})$	93.55	(0.000)
	$f(\ln p_K, g(\ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}), \ln p_{E_C})$	356.57	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}), \ln p_{E_G}, \ln p_{E_E})$	210.80	(0.000)
	$f(\ln p_K, \ln p_{E_C}, \ln p_{E_O}, g(\ln p_{E_G}, \ln p_{E_E}))$	325.31	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_G}), \ln p_{E_O}, \ln p_{E_E})$	256.52	(0.000)
	$f(\ln p_K, \ln p_{E_C}, \ln p_{E_G}, g(\ln p_{E_O}, \ln p_{E_E}))$	250.07	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_E}), \ln p_{E_O}, \ln p_{E_G})$	12.16	(0.007)
	$f(\ln p_K, \ln p_{E_C}, \ln p_{E_E}, g(\ln p_{E_O}, \ln p_{E_G}))$	91.24	(0.000)

Table I-16. Test Results of Separability (US)

Case	Separability Pattern	χ^2	*p*-value
Case 1	$f(g(\ln p_{K_I}, \ln p_{K_M}, \ln p_{K_B}), h(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}))$	60723.38	(0.000)
Case 2	$f(g(\ln p_{K_I}, \ln p_{K_M}, \ln p_{K_B}), \ln p_E)$	470.32	(0.000)
	$f(g(\ln p_{K_I}, \ln p_{K_M}), \ln p_{K_B}, \ln p_E)$	184.57	(0.000)
	$f(g(\ln p_{K_I}, \ln p_{K_B}), \ln p_{K_M}, \ln p_E)$	1261.25	(0.000)
	$f(g(\ln p_{K_M}, \ln p_{K_B}), \ln p_{K_I}, \ln p_E)$	89.81	(0.000)
Case 3	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}))$	128.12	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_G}), \ln p_{E_E})$	638.91	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}, \ln p_{E_E}), \ln p_{E_G})$	198.01	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_G}, \ln p_{E_E}), \ln p_{E_O})$	470.35	(0.000)
	$f(\ln p_K, g(\ln p_{E_O}, \ln p_{E_G}, \ln p_{E_E}), \ln p_{E_C})$	259.10	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_O}), \ln p_{E_G}, \ln p_{E_E})$	34.14	(0.000)
	$f(\ln p_K, \ln p_{E_C}, \ln p_{E_O}, g(\ln p_{E_G}, \ln p_{E_E}))$	982.23	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_G}), \ln p_{E_O}, \ln p_{E_E})$	595.12	(0.000)
	$f(\ln p_K, \ln p_{E_C}, \ln p_{E_G}, g(\ln p_{E_O}, \ln p_{E_E}))$	226.15	(0.000)
	$f(\ln p_K, g(\ln p_{E_C}, \ln p_{E_E}), \ln p_{E_O}, \ln p_{E_G})$	368.73	(0.000)
	$f(\ln p_K, \ln p_{E_C}, \ln p_{E_E}, g(\ln p_{E_O}, \ln p_{E_G}))$	133.44	(0.000)

6. Discussions and Implications

The Part I contemplates the assumption that capital and energy are weakly separable from each other. Applying Denny and Fuss (1977)'s method, the dataset of the manufacturing sectors of the ten OECD countries is analyzed.

For the analysis, components of energy and capital aggregates should be defined *in prior*. Synthesizing previous literatures on classification on this issue (BEA, 2003; Christensen and Jorgenson, 1969; Field and Grebenstein, 1980; Fuss, 1977; Garofalo and Malhotra, 1988; OECD, 2001; Pyo, 2003; Serletis et al., 2010b; SNA, 1993; Timmer et al., 2007), components of capital aggregate are defined as ICT assets, machinery, and buildings; and those of energy aggregate as coal, oil, gas, and electricity. Three cases on the separability are considered. The *Case 1* deals with whether capital and energy aggregates are weakly separable from each other. The *Case 2* examines whether any aggregate of the three capital assets can be consistent, and the *Case 3* whether any aggregate of the four energy sources can be consistent.

By cases, the separability patterns and their corresponding parameter restrictions are tested. Test results of the total sixteen separability patterns can be summarized as follows. First, it is not

appropriate to assume separability between energy and capital in every country analyzed. Second, any combination of the three capital assets are not weakly separable from each other in every country analyzed, either. Third, energy aggregate is not consistently derived except in Korea.

The above results imply that separability between energy and capital, which has been conventionally assumed in many applied studies of the KLEM model, is not theoretically permissible, in general. It proves that the assertion of Fuss (1977), which defended separability between energy and capital, is not available, in fact. Eventually, the results of Part I suggest that it is better to divide energy and capital into sub-inputs at the manageable level in the application of the KLEM model.

PART II. EFFECT OF CAPITAL INVESTMENT ON ENERGY DEMAND: ANALYSIS ON THE EXTENDED ENERGY SUB-MODEL

1. Introduction

In the application of the KLEM model, it is general to assume that the energy mix is not related to the capital investment. The concept of separability between energy and capital justifies this assumption. However, in the industrial sector, what kind of capital asset is invested may affect the choice of energy source, actually. The results of Part I, which empirically proved that energy and capital are not separable from each other, support this possibility. Namely, the investment of capital may have a direct influence on the interfuel substitutability.

The problem is whether the effect of capital investment in interfuel substitutability depends on the type of capital asset. For example, if the ICT assets are invested, the use of electricity may be accompanied. If the changes in the demands of different energy sources depend on the nature of invested capital assets, then it will be appropriate to consider these capital assets in an analysis of interfuel substitutability. Starting from this motivation, the Part II analyzes how the demands of the coal, oil, gas, and electricity are

differentiated by the investment in the individual capital asset.

For the analysis, the energy sub-model (Fuss, 1977), which is a sub-part of the KLEM model, is extended by adding a variable regarding the effect of capital investment. The original energy sub-model analyzes how the demands of different energy sources respond to their price changes. That is, it is a representative model for estimating interfuel substitutability econometrically, and has been widely used until these days (Steinbuks, 2012). However, when energy and capital are not weakly separable any more, the energy sub-model is needed to be revised because separability is a premise of the model. The extension of the energy sub-model was already tried in Considine (1989b), but his study does not consider the addition of a variable regarding capital investment. The part II suggests an extended energy sub-model which incorporates the effect of capital investment and compares this extended model with the energy sub-model.

There are few studies which have examined the effect of capital investment in the energy demand (Bernstein and Madlener, 2008; Cho et al., 2007; Collard et al., 2005). However, these studies overlook considering various components of capital and energy. They focused on estimating the impact of the investment in the ICT assets on the electricity demand. This part divides capital into sub-inputs as

much as possible, and investigates the effect of each capital asset on the demands of the individual demand. This effort can be also utilized as a reference for how to divide energy and capital into sub-elements in application the KLEM model.

The remainder of the Part II is organized as follows. In the next section, the extended energy sub-model and the measurement of interfuel substitutability are demonstrated. Section 3 describes how to divide capital into sub-inputs and their corresponding list of assets. Section 4 analyzes the effects of capital assets on the demands of coal, oil, gas, and electricity. Section 5 suggests the final version of the extended energy sub-model, compares the extended model with the original model, and explains interfuel substitutability derived by the extended model. Finally, the discussions and implications are summarized in Section 6.

2. Method

2. 1. Extended Energy Sub-Model

As in Fuss (1977), a production function with the KLEM model is assumed as follows

$$Y = f(x_K, x_L, x_E(x_{E_C}, x_{E_O}, x_{E_G}, x_{E_E}), x_M, t), \quad \text{(II-1)}$$

where Y is a gross output, x_K capital input, x_L labor input, x_E energy input, x_M material input, and t reflects technical change. Especially, $x_E(\cdot)$ is a homothetic aggregator function over n energy sources. Here, four energy sources, *i.e.*, coal (E_C), oil (E_O), gas (E_G), and electricity (E_E), are assumed. So, x_{E_C} is coal input, x_{E_O} oil input, x_{E_G} gas input, and x_{E_E} electricity input. The production function in Eq. (II-1) is weakly separable in energy from other input factors. Using duality theory (Shephard, 1953), the cost function corresponding to the production function in Eq. (II-1) is also weakly separable in energy from other inputs, and is given by

$$C = g(p_K, p_L, p_E(p_{E_C}, p_{E_O}, p_{E_G}, p_{E_E}), p_M, t, Y). \quad \text{(II-2)}$$

p_K is capital price, p_L labor price, $p_E(\cdot)$ an energy price aggregator function, and p_M material price. Similarly, p_{E_C} denotes coal price, p_{E_O} oil price, p_{E_G} gas price, and p_{E_E} electricity price. The energy price aggregator function $p_E(\cdot)$ represents an arbitrary unit cost function because it is also interpreted as the price per unit of energy.

So far, most literatures have approximated the energy price aggregator function using a flexible functional form. A translog function (Christensen et al., 1973), which has been most widely used, is applied in this part. A translog price aggregator function is written as

$$\ln p_E = \alpha_0 + \sum_i \beta_{E_i} \ln p_{E_i} + \frac{1}{2}\sum_i \sum_j \beta_{E_i E_j} \ln p_{E_i} \ln p_{E_j} \quad . \qquad \text{(II-3)}$$
$$i, j = C, O, G, E$$

Applying the Shephard's lemma to Eq. (II-3), the demand functions of the different energy sources are obtained in terms of cost shares in aggregate energy expenditure (Serletis et al., 2010a), and they are as follows

$$S_{E_i} = \frac{\partial \ln p_E(\cdot)}{\partial \ln p_{E_i}} = \beta_{E_i} + \sum_j \beta_{E_i E_j} \ln p_{E_i}, \quad i, j = C, O, G, E . \quad \text{(II-4)}$$

The Results of the Part I show that energy aggregate is not separable from capital aggregate. It means that the aggregation process of different energy sources is actually relevant to the investment in the capital assets. To capture the effect of capital investment, the Part II analyzes how the demands of different energy sources are differentiated by investment in various capital assets. In this context, a term denoting the investment in a certain kind of capital asset is added to Eq. (II-4). Then, demands functions for the individual energy sources are re-written as

$$S_{E_i} = \frac{\partial \ln p_E(\cdot)}{\partial \ln p_{E_i}} = \beta_{E_i} + \sum_j \beta_{E_i E_j} \ln p_{E_i} + \alpha_{E_i} \cdot RK_m, \quad \text{(II-5)}$$
$$i, j = C, O, G, E$$

where RK_m $(m = 1, \ldots, n)$ represents the share of m-th capital asset stock to the total capital stock[13]. This term allows us to observe

[13] In general, the capital stock increases according to the economic growth. Thus, to capture the effect of increases in the *m*-th capital stock among several types of capital assets, the share of the *m*-th capital stock to the total capital stock is employed as a variable.

the effect of investing the m-th capital asset on the demand of the i-th energy source.

Symmetry is imposed on Eq. (III-6) by the parameter restriction, $\beta_{ij} = \beta_{ji}$. And the assumption that the energy aggregator function is homogeneous of degree one in their prices, requires that the following parameter restrictions be satisfied;

$$\sum_i \beta_{E_i} = 1; \quad \sum_i \beta_{E_i E_j} = \sum_i \beta_{E_j E_i} = \sum_i \alpha_{E_i} = 0 \quad i, j = C, O, G, E \qquad \text{(II-6)}$$

Due to the adding-up condition shown in Eq. (II-6), estimation of the system of cost share equations shown in Eq. (II-5) yields singularity. Thus, the procedure involves dropping one of the equations from the system of the demand functions. With subtracting a certain input's cost share equation, the system of three cost share equations is estimated instead.

2. 2. Measurement of Interfuel Substitutability

Two measures of interfuel substitutability are used in this study; the own-price elasticity η_{ii} and the Morishima elasticity of

substitution (MES) σ_{ij}^{m}.

The own-price elasticity measures actual percentage changes in the demand of i-th energy source from the changes in its own price. If the estimates of η_{ii} is negative, the law of demand is satisfied. In case of translog approximation, it can be calculated as follows:

$$\eta_{ii} = \frac{\beta_{E_iE_i}}{S_{E_i}} + S_{E_i} - 1, \quad i = C, O, G, E . \tag{II-7}$$

The MES is developed independently by Morishima (1967) and Blackorby and Russell (1989). It is informative when there are more than two inputs. With more than two inputs, interfuel substitutability becomes complex and depends on things like the direction taken towards the point of approximation. The MES between i-th energy source and j-th energy source is expressed as

$$\sigma_{ij}^{m} = \eta_{ij} - \eta_{jj} = \frac{\beta_{E_iE_j}}{S_{E_i}} - \frac{\beta_{E_jE_j}}{S_{E_j}} + 1, \quad i, j = C, O, G, E . \tag{II-8}$$

The MES measures the percentage changes in the ratio of i-th energy source to j-th energy source when the price of j-th energy

source alters. If $\sigma_{ij}^{m} > 0$ (that is, if increasing the price of j-th energy source increases the optimal quantity of i-th energy source relative to the optimal quantity of input of j-th energy source), i-th energy source will substitute j-th energy source. If $\sigma_{ij}^{m} < 0$, i-th energy source will complement j-th energy source. The MES can measure asymmetric substitutability between two inputs. Namely, it helps us to observe the main direction of substitution.

3. Data

3. 1. List of Capital Assets

To analyze the effect of capital investment in the demands of different energy sources, division of capital into sub-inputs should be followed. In the Part I, this thesis defines initially the components of capital aggregate: ICT assets (K_I), machinery (K_M), and buildings (K_B), based on the previous studies (BEA, 2003; Christensen and Jorgenson, 1969; Field and Grebenstein, 1980; Garofalo and Malhotra, 1988; OECD, 2001; Pyo, 2003; SNA, 1993; Timmer et al., 2007). However, this definition is insufficient to measure the effect of a capital asset on the individual energy source. The insufficiency results from that this definition classifies still capital assets, which affect differently on the demands of energy sources, within a group.

Given data availability, this part divides capital into sub-input at the utmost level. That is, capital is divided into six groups, *i.e.*, ICT assets (K_1), transport equipment (K_2), other machinery (K_3), other assets (K_4), non-residential structures (K_5), and residential structures (K_6). In other words, ‘machinery’ is divided into ‘transport equipment’, ‘other machinery’, and ‘other assets’. And ‘buildings’ is divided into ‘non-residential structures’ and ‘residential structures’.

Their relationships are graphically described in Figure II-1. The detailed list of assets of six groups is also presented in Table II-1.

Figure II-1. Relationships among Capital Assets

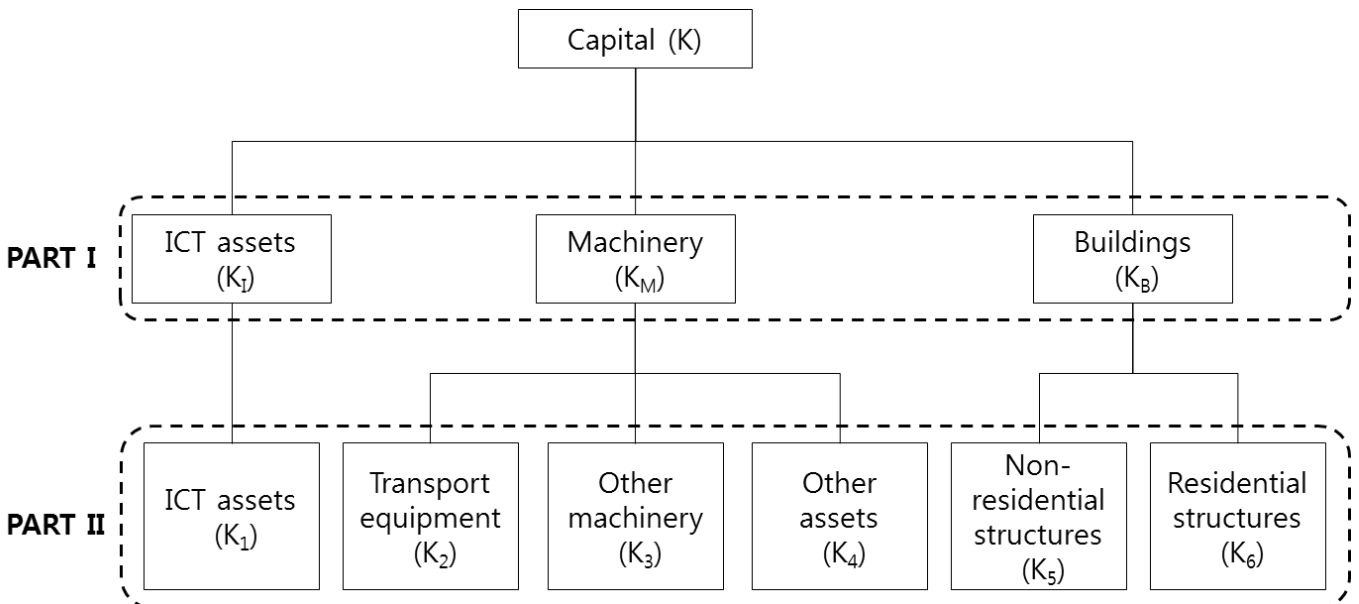


Table II-1. Detailed List of Capital Assets

Classification of Capital Assets		**Asset list**
Part I	Part II (This chapter)	
ICT assets (K_I)	ICT assetsl (K_1)	Computing equipment; Communication equipment; Software
Machinery (K_M)	Transport equipment (K_2)	Trucks, buses, and truck trailers; Autos; Aircraft; Ships and Boats, Railroad equipment
	Other machinery and equipment (K_3)	Instruments; Photocopy and related equipment; Nuclear fuel; Other fabricated metal products; Steam engines and turbines; Internal combustion engines; Metalworking machines; Special industrial machinery; General industrial, including materials handling equipment; Electrical transmissions, distributions, and industrial apparatus; other electrical equipment
	Other assets (K_4)	-
Buildings (K_B)	Total non-residential structures (K_5)	Industrial buildings; Mobile offices; Office buildings; Commercial warehouses; other commercial buildings; Religious buildings; Educational buildings; Hospital and institutional buildings; Hotels and motels; Amusement and recreational buildings; All other nonfarm buildings; Railroad replacement track; electric light and power, gas, petroleum pipeline
	Residential structures (K_6)	Unit structure; Manufactured home

[a] The list is made up referring the BEA (2003) and Timmer et al. (2007).

3. 2. Data Description

To analyze the extended energy sub-model in Eq. (II-5), cost shares and prices for the four energy sources, *i.e.*, coal (E_C), oil (E_O), gas (E_G), and electricity (E_E), are needed. Also, capital stock data for the six groups should be prepared to capture the effect of the capital investment. This section describes the dataset which are used for the estimation of the extended energy sub-model. For general discussion, the manufacturing sectors of the ten OECD countries are analyzed: Australia; Austria; Denmark; Finland; Japan; Korea; Netherlands; UK; and US.

Data of four energy sources, *i.e.*, coal (E_C), oil (E_O), gas (E_G), and electricity (E_E), are gathered from the *Energy Prices and Taxes* series published by the IEA (International Energy Agency) (IEA, 2012), the *Energy Balances of OECD Countries* series also published by the IEA (IEA, 2011), and the EU KLEMS consortium. The *Energy Prices and Taxes* series provides price indices of four energy sources (p_{E_i} , $i = C, O, G, E$), and the *Energy Balances of OECD Countries* series consumptions of those energy sources (x_{E_i} , $i = C, O, G, E$). The EU KLEMS consortium gives the data of total energy cost of the manufacturing sector. Combining these data, cost shares for coal, oil,

gas, and electricity (S_{E_i}, $i = C, O, G, E$) are derived. And the time-series data of prices are normalized based on 1990=1.

Data of six capital assets, *i.e.*, ICT assets (K_1), transport equipment (K_2), other machinery and equipment (K_3), other assets (K_4), total non-residential structures (K_5), and residential structures (K_6), are collected from the database of the EU KLEMS consortium. The consortium provides 'real fixed capital stock in 1995 prices' for the six groups of capital assets in the local currency. Using this dataset, the share of m-th capital asset stock to the total capital stock ($RK_m, m = 1, \ldots, 6$) are calculated.

Sample period is slightly different by country because of data availability and different adoption of gas. For Australia, Austria, Finland, Italy, Netherlands, UK, and US, the sample period is from 1980 to 2007 ($T = 28$), for Denmark from 1984 to 2007 ($T = 24$), for Japan from 1980 to 2006 ($T = 27$), and for Korea from 1985 to 2007 ($T = 23$). Sample mean and standard deviation of RK_m is presented in Table II-2. Those of cost shares and price indices of four energy sources are also presented in Table II-3.

Table II-2. Sample Mean Stocks for Six Capital Types

	ICT assets (K_1)	Transport equipment (K_2)	Other machinery (K_3)	Other assets (K_4)	Non-residential structures (K_5)	Residential Structures (K_6)
Australia	0.054 (0.040)	0.067 (0.008)	0.486 (0.016)	-	0.393 (0.024)	-
Austria	0.025 (0.025)	0.024 (0.002)	0.487 (0.019)	-	0.464 (0.018)	-
Denmark	0.062 (0.042)	0.029 (0.002)	0.465 (0.024)	-	0.444 (0.020)	-
Finland	0.044 (0.030)	0.025 (0.010)	0.470 (0.025)	-	0.460 (0.038)	-
Italy	0.027 (0.009)	0.025 (0.002)	0.497 (0.009)	0.005 (0.001)	0.446 (0.012)	-
Japan	0.029 (0.015)	0.020 (0.005)	0.357 (0.021)	0.116 (0.021)	0.478 (0.058)	-
Korea	0.036 (0.011)	0.069 (0.010)	0.538 (0.012)	-	0.313 (0.018)	0.043 (0.000)
Netherlands	0.047 (0.025)	0.019 (0.003)	0.454 (0.021)	0.046 (0.005)	0.433 (0.045)	0.002 (0.000)
UK	0.053 (0.033)	0.043 (0.018)	0.569 (0.018)	-	0.335 (0.010)	-
US	0.069 (0.047)	0.038 (0.005)	0.481 (0.015)	0.006 (0.003)	0.405 (0.0310)	-

[a] Standard deviations are presented in the parenthesis.

Table II-3. Sample Mean Prices and Cost Shares for Four Energy Sources

	Price				Cost Share			
	Coal (p_{E_C})	Oil (p_{E_O})	Gas (p_{E_G})	Electricity (p_{E_E})	Coal (S_{E_C})	Oil (S_{E_O})	Gas (S_{E_G})	Electricity (S_{E_E})
Australia	1.777 (0.827)	1.743 (0.473)	1.732 (0.686)	1.607 (0.576)	0.048 (0.012)	0.066 (0.089)	0.200 (0.018)	0.586 (0.086)
Austria	0.870 (0.010)	0.924 (0.162)	0.942 (0.139)	0.831 (0.086)	0.046 (0.020)	0.065 (0.028)	0.183 (0.024)	0.705 (0.034)
Denmark	1.234 (0.571)	1.260 (0.705)	1.100 (0.288)	1.308 (0.421)	0.040 (0.015)	0.189 (0.140)	0.258 (0.087)	0.513 (0.079)
Finland	1.788 (0.829)	2.040 (1.228)	1.921 (0.792)	1.682 (0.794)	0.115 (0.023)	0.288 (0.120)	0.105 (0.016)	0.492 (0.127)
Italy	1.485 (0.591)	1.649 (0.768)	1.561 (0.685)	1.320 (0.415)	0.016 (0.005)	0.221 (0.086)	0.098 (0.024)	0.664 (0.069)
Japan	1.015 (0.225)	1.243 (0.465)	1.038 (0.108)	1.041 (0.143)	0.045 (0.013)	0.173 (0.045)	0.032 (0.010)	0.749 (0.044)
Korea	1.670 (0.732)	3.384 (2.463)	3.176 (2.404)	1.642 (0.430)	0.016 (0.002)	0.328 (0.049)	0.032 (0.034)	0.624 (0.025)
Netherlands	1.203 (0.396)	1.171 (0.410)	1.401 (0.619)	1.359 (0.465)	0.021 (0.008)	0.109 (0.044)	0.301 (0.025)	0.569 (0.049)
U.K.	1.096 (0.320)	1.687 (0.672)	1.439 (0.625)	1.269 (0.278)	0.066 (0.043)	0.152 (0.037)	0.233 (0.032)	0.549 (0.068)
U.S.	0.861 (0.155)	1.062 (0.527)	1.257 (0.676)	0.850 (0.151)	0.033 (0.014)	0.140 (0.097)	0.313 (0.078)	0.514 (0.133)

[a] Standard deviations are presented in the parenthesis.

4. Effects of Capital Assets on Energy Demand

Estimation of Eq. (II-5) by capital type gives parameter estimates of α_i ($i = C, O, G, E$). α_i measures how the relative stock of m-th capital asset ($m = 1, \ldots, n$) affects the cost shares for coal, oil, gas, and electricity. The estimation is performed by the TSP 5.1 package using the LSQ procedure (Hall and Cummins, 2009), which provides seemingly unrelated regression estimates (Zellner, 1962)[14]. All parameter estimates of Eq. (II-5) are presented in the Section 1 of Appendix II.

Effects of the stock of the ICT assets (K_1) on the cost shares for coal, oil, gas, and electricity are presented in Table II-4. Among 40 estimates[15], 36 estimates are statistically significant at the 10% level. That is, it seems that the investment in the ICT assets has influenced upon the choice of energy source. Particularly, it increases the electricity demand while decrease both the coal and oil demands. On the other hand, it has an ambiguous effect on the gas demand. These

[14] The estimation method, seemingly unrelated regression, is explained in the Section 6 of the second chapter named as 'THEORETICAL FOUNDATION: KLEM MODEL'.

[15] Because there are ten countries and four energy sources, the effect of the ICT assets are measured through 40 estimates.

results correspond to the common expectation on the effect of the investment in the ICT assets. And, the estimates of the effect of the ICT asset investment in the electricity demand correspond with the studies which investigated this matter (Bernstein and Madlener, 2008; Cho et al., 2007; Collard et al., 2005).

Effects of the stock of the transport equipment (K_2) on the cost shares for the energy sources are presented in Table II-5. 32 parameter estimates are statistically significant at the 10% level. On the contrary, in Korea, the effects of the stock of the transport equipment are not significant for any kind of energy sources at all. The results show that the investment in the transport equipment increases the oil demand as well as the coal while decreases the electricity demand. It seems to correspond with the attribute of the transport equipment, which primarily accompanies the use of coal and oil. However, an exceptional phenomenon is observed in Japan.

Effects of the stock of the other machinery (K_3) on the cost shares for the energy sources are presented in Table II-6. 28 estimates are statistically significant at the 10% level. However, in UK, the effects of the stock of the other machinery are not significant for any kinds of energy sources at all. The investment in the other machinery seems to contribute increasing the electricity demand, except Austria and US. It also has ambiguous effect on the demands of the other

energy sources. Seeing at assets belonging to the other machinery shown in Table II-1, actually is it related with the use of all kinds of energy sources. On the other hand, the effect of the stock of the other machinery on the electricity demand seems to be reasonable because many electricity-using facilities have been adopted recently.

Effects of the stock of the other assets (K_4) on the cost shares for the energy sources are presented in Table II-7. These effects are only measured in Italy, Japan, Netherlands, and US where the data of the stock of the other assets exist. Among 16 estimates, 13 estimates are statistically significant at the 10% level. The estimates reveal that the investment in the other assets decreases the oil demand while increases the electricity demand. However, it is difficult to continue further discussion because the property of assets which belongs to this group cannot be identified, and the sample size is small, either.

Effects of the stock of the non-residential structures (K_5) on the cost shares for the energy sources are presented in Table II-8. Among 40 estimates, 35 estimates are statistically significant at the 10% level. Thus, the investment in the non-residential structure is considered to affect the choice of energy source throughout the industry. In specific, it increases the coal and oil demands while decreases the electricity demand. Since assets belonging to the group of the non-residential structures mainly involve the use of electricity or gas (See Table II-1),

this result does not correspond with our expectation. This paradoxical phenomenon seems to result from the decrease in the stock of the non-residential structures in spite of the increase in the electricity demand for the last three decades. That is to say, the non-residential structures may use electricity but not contribute to the increase in the electricity demand.

Finally, effects of the stock of the residential structures (K_6) on the cost shares for the energy sources are presented in Table II-9. The analysis is only conducted on the data of Korea and Netherlands because of data availability. Among 8 estimates, half the estimates are statistically significant at the 10% level. Thus, it is not likely that the investment in the residential structure have affected the choice of energy source in the manufacturing sector. However, due to the shortage of the samples, the generalization of the result seems to be hard.

Summarizing these results is as follows. First, the capital assets which have a clear impact on the demands of coal, oil, gas, and electricity are ICT assets (K_1) and transport equipment (K_3). Second, the six groups of capital assets can be finally classified into the two types: the capital which increases the demand of electricity (EK, K_{EK}); and the capital which does not (NK, K_{NK}). The ICT assets, other machinery and other assets belong to the EK, and the transport

equipment, non-residential structures, and residential structures to the NK.

Table II-4. Effect of the ICT Assets (K_1) on Energy Cost Share

	Australia		**Austria**		**Denmark**		**Finland**		**Italy**	
	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value
Coal	-0.268	(0.000)	-0.539	(0.000)	-0.104	(0.003)	-0.208	(0.125)	-0.490	(0.000)
Oil	-1.509	(0.000)	-0.920	(0.000)	-1.764	(0.000)	-1.864	(0.078)	-10.848	(0.000)
Gas	0.276	(0.000)	0.890	(0.000)	1.399	(0.000)	0.367	(0.052)	2.748	(0.000)
Electricity	1.501	(0.000)	0.568	(0.000)	0.469	(0.000)	1.705	(0.064)	8.590	(0.000)
	Japan		**Korea**		**Netherlands**		**UK**		**US**	
	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value
Coal	-0.056	(0.386)	-0.154	(0.285)	-0.080	(0.316)	-0.171	(0.341)	-0.106	(0.094)
Oil	-1.608	(0.000)	-6.381	(0.000)	-0.890	(0.009)	-1.132	(0.000)	-0.970	(0.000)
Gas	0.398	(0.000)	1.394	(0.000)	-1.215	(0.000)	-0.550	(0.000)	-0.017	(0.794)
Electricity	1.266	(0.000)	5.141	(0.000)	2.185	(0.000)	1.853	(0.000)	1.094	(0.000)

Table II-5. Effect of the Transport Equipment (K_2) on Energy Cost Share

	Australia		**Austria**		**Denmark**		**Finland**		**Italy**	
	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value
Coal	0.903	(0.000)	6.201	(0.000)	-0.873	(0.376)	1.221	(0.004)	1.125	(0.000)
Oil	4.325	(0.012)	11.320	(0.000)	36.694	(0.000)	13.762	(0.000)	33.436	(0.000)
Gas	-0.988	(0.000)	-9.877	(0.000)	-30.738	(0.000)	-2.579	(0.000)	-7.918	(0.000)
Electricity	-4.240	(0.017)	-7.645	(0.000)	-5.0783	(0.002)	-12.404	(0.000)	-26.643	(0.000)
	Japan		**Korea**		**Netherlands**		**UK**		**US**	
	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value
Coal	0.699	(0.118)	-0.157	(0.575)	-0.206	(0.575)	0.698	(0.067)	-1.176	(0.009)
Oil	-4.519	(0.007)	1.519	(0.657)	11.031	(0.004)	2.299	(0.000)	8.771	(0.000)
Gas	1.535	(0.001)	-0.637	(0.476)	6.705	(0.000)	0.549	(0.000)	0.828	(0.215)
Electricity	2.285	(0.059)	-0.725	(0.803)	-17.530	(0.000)	-3.546	(0.000)	-8.423	(0.000)

Table II-6. Effect of the Other Machinery (K_3) on Energy Cost Share

	Australia		**Austria**		**Denmark**		**Finland**		**Italy**	
	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value
Coal	0.006	(0.971)	0.803	(0.000)	0.164	(0.005)	-0.052	(0.669)	4.922	(0.000)
Oil	-0.080	(0.936)	1.005	(0.000)	3.131	(0.000)	-4.868	(0.000)	-9.362	(0.000)
Gas	0.030	(0.869)	-1.448	(0.000)	-2.372	(0.000)	0.835	(0.000)	2.168	(0.000)
Electricity	0.044	(0.964)	-0.359	(0.091)	-0.923	(0.000)	4.085	(0.000)	7.466	(0.001)
	Japan		**Korea**		**Netherlands**		**UK**		**US**	
	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value
Coal	-0.020	(0.706)	-0.008	(0.849)	0.097	(0.203)	-0.077	(0.803)	-0.329	(0.003)
Oil	-1.072	(0.000)	-1.045	(0.066)	-2.043	(0.000)	-1.471	(0.094)	3.249	(0.000)
Gas	0.269	(0.000)	0.360	(0.002)	-0.624	(0.001)	0.604	(0.195)	0.039	(0.870)
Electricity	0.822	(0.000)	0.692	(0.168)	2.570	(0.000)	0.944	(0.382)	-2.959	(0.000)

Table II-7. Effect of the Other Assets (K_4) on Energy Cost Share

	Australia		**Austria**		**Denmark**		**Finland**		**Italy**	
	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value
Coal	-	-	-	-	-	-	-	-	-3.024	(0.000)
Oil	-	-	-	-	-	-	-	-	-74.493	(0.000)
Gas	-	-	-	-	-	-	-	-	17.533	(0.000)
Electricity	-	-	-	-	-	-	-	-	59.984	(0.000)
	Japan		**Korea**		**Netherlands**		**UK**		**US**	
	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value
Coal	0.004	(0.953)	-	-	0.585	(0.037)	-	-	-2.716	(0.008)
Oil	-1.114	(0.000)	-	-	-9.536	(0.000)	-	-	-14.631	(0.000)
Gas	0.296	(0.000)	-	-	-1.750	(0.145)	-	-	-0.482	(0.616)
Electricity	0.814	(0.000)	-	-	10.701	(0.000)	-	-	17.819	(0.000)

Table II-8. Effect of the Non-Residential Structures (K_5) on Energy Cost Share

	Australia		**Austria**		**Denmark**		**Finland**		**Italy**	
	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value
Coal	0.396	(0.000)	0.971	(0.000)	0.193	(0.005)	0.084	(0.433)	0.192	(0.000)
Oil	2.904	(0.000)	1.743	(0.000)	3.675	(0.000)	3.155	(0.000)	6.469	(0.000)
Gas	-0.554	(0.000)	-0.955	(0.015)	-3.483	(0.000)	-0.562	(0.000)	-1.381	(0.000)
Electricity	-2.745	(0.000)	-1.759	(0.000)	-0.386	(0.260)	-2.677	(0.000)	-5.289	(0.000)
	Japan		**Korea**		**Netherlands**		**UK**		**US**	
	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value
Coal	0.011	(0.595)	0.154	(0.000)	-0.033	(0.544)	0.185	(0.390)	0.199	(0.012)
Oil	0.414	(0.000)	1.982	(0.001)	0.832	(0.000)	2.844	(0.000)	1.371	(0.000)
Gas	-0.117	(0.000)	-0.424	(0.007)	0.538	(0.000)	0.914	(0.001)	0.055	(0.561)
Electricity	-0.308	(0.000)	-1.712	(0.000)	-1.382	(0.000)	-3.942	(0.000)	-1.625	(0.000)

Table II-9. Effect of the Residential Structures (K_6) on Energy Cost Share

	Australia		**Austria**		**Denmark**		**Finland**		**Italy**	
	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value
Coal	-	-	-	-	-	-	-	-	-	-
Oil	-	-	-	-	-	-	-	-	-	-
Gas	-	-	-	-	-	-	-	-	-	-
Electricity	-	-	-	-	-	-	-	-	-	-
	Japan		**Korea**		**Netherlands**		**UK**		**US**	
	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value
Coal	-	-	-0.148	(0.000)	-74.382	(0.002)	-	-	-	-
Oil	-	-	0.386	(0.447)	144.340	(0.621)	-	-	-	-
Gas	-	-	-0.151	(0.036)	227.578	(0.018)	-	-	-	-
Electricity	-	-	-0.088	(0.850)	-297.54	(0.356)	-	-	-	-

5. Comparison of the Extended Energy Sub-Model with the Energy Sub-Model

The results of the Section 4 confirmed that the demands of coal, oil, gas, and electricity are determined according to the type of the invested capital asset. They implies that the investment in the capital assets as well as the price changes in the energy sources should be included as explanatory variables the energy sub-model. That is, they support the extended energy sub-model which is firstly constructed by this thesis. The inclusion of the capital stock as an explanatory variable of the energy sub-model is also justified by the results of Part I, which showed that energy and capital are not weakly separable from each other. This section proposes the final version of the extended energy sub-model, which embodies the effect of capital investment. Then, it compares this extended energy sub-model with the original energy sub-model. In particular, the performance and the derived interfuel substitutability of the two models are intensively compared.

If the six groups of capital assets are simultaneously included in

the model, the problem of multi-collinearity[16] will occur. So, the capital assets are classified according to their effects on the electricity demand by utilizing the results of the Section 4: the capital which increases the demand of electricity (EK, K_{EK}); and the capital which does not (NK, K_{NK}). Applying this categorization, the final version of the extended energy sub-model is defined as

$$S_{E_i} = \frac{\partial \ln p_E(\cdot)}{\partial \ln p_{E_i}} = \beta_{E_i} + \sum_j \beta_{E_i E_j} \ln p_{E_i} + \alpha_{E_i} \cdot RK_{EK} \quad . \qquad \text{(II-9)}$$
$$i, j = C, O, G, E$$

Here, RK_{EK} denotes the share of the EK stock to the total capital stock[17]. Because the share of capital stock is employed as explanatory variables, only one of the two capital types is included[18].

Parameter estimates of the original energy sub-model shown in Eq. (II-5) and the extended energy sub-model shown in Eq. (II-9) are presented in the Section 2 of Appendix II. Both estimations are

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[16] Multi-collinearity arises when there is a strong linear relationship among two or more independent variables. Because it violates the basic assumption of regression, it should be resolved in the construction of the model.

[17] The Divisia index (Diewert, 1976) is used for integrating various capital assets.

[18] The results may be same when RK_{NK}, *i.e.* the share of the NK stock to the total capital stock, is included instead of RK_{EK}.

performed by the TSP 5.1 package using the LSQ procedure, which provides seemingly unrelated regression estimates (Zellner, 1962).

5. 1. Comparison of the Performance

To compare the performances of the two models, concavity, autocorrelation, and explanatory power are checked.

First, the concavity violations of the both models are compared, and they are presented in Table II-10. As required by the producer's theory, the conditional input demand function of the i-th energy source should satisfy concavity (Varian, 1992). Concavity requires that the matrix of second partial derivatives of cost with respect to prices, *i.e.*, the Hessian matrix, be negative semi-definite. It is also a sufficient condition for negative own-price elasticities (Considine, 1989a).

Regardless of the type of model, concavity violations are observed. Although, concavity is a key assumption of duality theorem, concavity violations have been observed many empirical studies applying the KLEM model. There are even some literatures on dealing the issue of concavity violations (Diewert and Wales, 1987; Feng and Serletis, 2008; Moschini, 1999; Ryan and Wales, 1998, 2000).

With the original energy sub-model, concavity is violated at most of the sample points in every country analyzed. With the extended energy sub-model, the concavity violations are decreased in Australia, Austria, Japan, and Korea but on the other hand, the opposite phenomenon occurs in Italy. In the other countries, violations of concavity with the energy sub-model are same as those with the extended model. Thus, it is likely that the extended energy sub-model tends to improve concavity although there is an exceptional case.

Table II-10. Comparison of Concavity Violations

	Original energy sub-model	**Extended energy sub-model**
Australia	28	2
Austria	26	18
Denmark	28	28
Finland	28	28
Italy	18	20
Japan	28	27
Korea	28	20
Netherlands	28	28
UK	28	28
US	28	28

Second, the level of autocorrelation, which tells inconsistency of the parameter estimates (Johnston and DiNardo, 2007), is checked. Since this thesis uses the aggregate time series data, the problem of

autocorrelation due to non-stationarity may occur (Feng and Serletis, 2008). The Durbin-Watson statistic (Durbin and Watson, 1950, 1951), which will be small for positively autocorrelated and approach two for zero correlation, is used for judging the level of autocorrelation. Estimates of the Durbin-Watson statistic of the two models are summarized in Table II-11.

Regardless of the type of model, the problem of positive autocorrelation occurs generally in all estimates, either. The positive autocorrelation has been typically permitted in the empirical study of the KLEM model analyzing time series data (Andrikopoulos et al., 1989; Christopoulos, 2000; Considine, 1989b; Considine, 1990; Hall, 1986; Serletis et al., 2010b; Truong, 1985; Urga and Walters, 2003). In Australia, Austria, Italy, Japan, and US, the positive autocorrelation of all the estimating equations is mitigated with the extended energy sub-model. In the other countries, the positive autocorrelations of two equations are mitigated while that of the other equation is deteriorated.

Table II-11. Comparison of the Durbin-Watson Statistic

Dependent variable	Energy sub-model			Extended energy sub-model		
	S_{E_C}	S_{E_O}	S_{E_G}	S_{E_C}	S_{E_O}	S_{E_G}
Australia	0.256	0.141	0.441	1.297	0.242	0.595
Austria	0.256	0.281	0.211	0.349	0.484	0.327
Denmark	0.859	0.246	0.341	0.700	0.293	0.418
Finland	1.170	0.118	0.136	1.022	0.364	0.394
Italy	0.695	0.043	0.071	1.671	0.635	0.545
Japan	0.900	0.277	0.166	0.932	1.815	0.625
Korea	0.469	0.656	0.449	0.837	0.539	0.606
Netherlands	1.005	1.121	0.482	0.940	1.756	0.856
UK	1.066	0.206	0.792	0.993	0.947	1.091
US	0.913	0.354	1.540	1.070	1.316	1.636

[a] Because of singularity, the equation of which the dependent variable is the cost share for electricity is excluded. Thus, the Durbin-Watson statistic where the dependent variable is cost share for electricity is not contained in this table.

Third, the explanatory power of the model, which is represented as R^2, is considered. R^2 may be interpreted as the proportion of the variation in the demands of the four energy sources attributable to the linear regression on the explanatory variables (Johnston and DiNardo, 2007). Estimates of the Durbin-Watson statistic of the two models are summarized in Table II-12.

Table II-12. Comparison of R^2

Dependent variable	Original energy sub-model			Extended energy sub-model		
	S_{E_C}	S_{E_O}	S_{E_G}	S_{E_C}	S_{E_O}	S_{E_G}
Australia	0.253	0.143	0.190	0.946	0.740	0.674
Austria	0.248	0.095	0.082	0.581	0.711	0.125
Denmark	0.883	0.559	0.234	0.898	0.775	0.622
Finland	0.696	0.007	0.275	0.702	0.682	0.507
Italy	0.645	0.020	0.582	0.803	0.884	0.936
Japan	0.905	0.693	0.791	0.909	0.957	0.925
Korea	0.283	0.530	0.938	0.453	0.691	0.966
Netherlands	0.741	0.113	0.034	0.756	0.538	0.530
UK	0.941	0.204	0.769	0.947	0.876	0.835
US	0.892	0.736	0.972	0.915	0.941	0.974

[a] Because of singularity, the equation of which the dependent variable is the cost share for electricity is excluded. Thus, R^2 where the dependent variable is cost share for electricity is not contained in this table.

In every country analyzed, R^2 of the extended energy sub-model is greater than that of the original energy sub-model, although the degree of greatness varies. Namely, the explanatory power increases in the extended energy sub-model. Although the increases in R^2 are generally expected when an explanatory variable is added, those shown in Table II-12 is considerably high. It supports the effectiveness of the addition of RK_{EK}.

5. 2. Interfuel Substitutability

Interfuel substitutability, which is derived by the original energy sub-model as well as the final version of the extended energy sub-model, are described in Table II-3 to II-22 by country. In the diagonal terms, own-price elasticities calculated by Eq. (II-7) are described while the MESs calculated by Eq. (II-8) in the off-diagonal terms. Compared to the original energy sub-model, features of interfuel substitutability, *i.e.*, the direction and the magnitude of substitution, are changed in most of the countries when the extended model is applied. However, a special tendency of changes is not found. Estimates of elasticities of substitution with the extended model show that it is likely that energy sources tends to be not easily substituted by other energy source in countries with high energy independence, such as, Denmark, Netherlands, UK, and US.

Table II-13. Elasticity of Substitution (Australia)

Energy sub-model

	Coal		Oil		Gas		Electricity	
Coal	-0.389	(-3.377**)	-0.253	(-0.211)	-0.795	(-2.961**)	-0.879	(-0.815)
Oil	0.931	(4.921**)	1.971	(1.020)	-0.191	(-0.439)	-2.667	(-1.236)
Gas	0.200	(1.514)	-2.128	(-0.969)	-0.072	(-1.290)	0.002	(0.158)
Electricity	0.356	(2.209**)	-2.496	(-1.081)	0.213	(2.650**)	0.417	(1.074)

Extended energy sub-model

	Coal		Oil		Gas		Electricity	
Coal	-0.242	(-5.741**)	1.484	(3.048**)	-0.161	(-1.197)	-0.127	(-0.442)
Oil	0.487	(7.030**)	-0.697	(-1.225)	0.495	(3.266**)	0.214	(0.357)
Gas	0.165	(3.735**)	0.931	(1.461)	-0.198	(-4.219**)	0.100	(1.004)
Electricity	0.229	(4.787**)	0.758	(1.028)	0.208	(3.344**)	-0.059	(-0.462)

[a] In parentheses, t-statistic is presented.

[b] ** and * means significance at the 5% and 10 % levels, respectively.

Table II-14. Elasticity of Substitution (Austria)

Energy sub-model

	Coal		Oil		Gas		Electricity	
Coal	0.506	(0.386)	-0.650	(-0.790)	3.697	(2.741**)	-2.604	(-2.824**)
Oil	-0.609	(-0.404)	0.506	(0.445)	2.147	(2.303**)	-1.096	(-1.019)
Gas	-0.011	(0.174)	-0.290	(-0.132)	-1.472	(-3.276**)	0.743	(3.678**)
Electricity	-0.645	(-0.553)	-0.582	(-0.516)	0.499	(0.017)	0.060	(0.306)

Extended energy sub-model

	Coal		Oil		Gas		Electricity	
Coal	0.365	(0.100)	0.859	(2.044**)	0.894	(1.531)	0.165	(0.198)
Oil	-0.881	(-0.360)	-1.581	(-3.443**)	0.250	(0.290)	2.548	(5.382**)
Gas	-0.254	(-0.042)	1.538	(2.316**)	-0.419	(-1.017)	0.634	(2.146**)
Electricity	-0.365	(-0.096)	1.770	(3.759**)	0.512	(1.133)	-0.282	(-3.413**)

[a] In parentheses, t-statistic is presented.

[b] ** and * means significance at the 5% and 10 % levels, respectively.

Table II-15. Elasticity of Substitution (Denmark)

Energy sub-model

	Coal		Oil		Gas		Electricity	
Coal	0.588	(3.484**)	-2.618	(-2.202**)	-3.550	(0.585)	-1.182	(-8.377**)
Oil	-0.731	(-3.636**)	2.065	(2.273**)	-6.509	(-2.997**)	-0.111	(-0.622)
Gas	-0.214	(-2.057**)	-5.604	(-2.536**)	4.595	(3.037**)	-1.533	(-2.087**)
Electricity	-0.661	(-4.133**)	-2.026	(-2.025**)	-4.664	(-3.178**)	0.103	(3.799**)

Extended energy sub-model

	Coal		Oil		Gas		Electricity	
Coal	0.762	(8.032**)	-1.598	(-2.528**)	0.628	(1.811*)	-0.847	(-5.273**)
Oil	-0.938	(-7.707**)	0.914	(1.153)	-3.830	(-1.828*)	-0.205	(-1.265)
Gas	-0.573	(-6.471**)	-2.358	(-1.311)	3.137	(2.262**)	-2.042	(-3.102**)
Electricity	-0.807	(-8.284**)	-0.885	(-0.949)	-3.281	(-2.693**)	0.161	(3.373**)

[a] In parentheses, t-statistic is presented.

[b] ** and * means significance at the 5% and 10 % levels, respectively.

Table II-16. Elasticity of Substitution (Finland)

Energy sub-model

	Coal		Oil		Gas		Electricity	
Coal	0.792	(3.221**)	0.414	(0.989)	0.287	(9.458**)	0.322	(1.141)
Oil	-1.086	(-4.061**)	-1.051	(-2.979**)	0.473	(5.722**)	1.637	(3.897**)
Gas	-0.758	(-3.057**)	1.613	(3.232**)	-0.257	(-10.65**)	0.169	(2.630**)
Electricity	-0.845	(-2.853**)	1.697	(3.265**)	0.172	(13.30**)	-0.508	(-3.711**)

Extended energy sub-model

	Coal		Oil		Gas		Electricity	
Coal	0.646	(2.641**)	-1.241	(-3.341**)	0.069	(1.202)	-0.330	(-1.346)
Oil	-0.879	(-3.068**)	0.742	(2.604**)	-0.021	(-0.013)	-0.603	(-2.022**)
Gas	-0.657	(-2.682**)	-0.959	(-2.387**)	-0.080	(-2.563**)	0.113	(2.849**)
Electricity	-0.686	(-2.388**)	-0.959	(-2.435**)	0.143	(4.360**)	0.194	(1.987**)

[a] In parentheses, t-statistic is presented.

[b] ** and * means significance at the 5% and 10 % levels, respectively.

Table II-17. Elasticity of Substitution (Italy)

Energy sub-model

	Coal		Oil		Gas		Electricity	
Coal	-0.067	(-0.671)	0.011	(0.163)	-0.841	(-1.112)	1.360	(4.182**)
Oil	0.047	(0.596)	-0.277	(-0.796)	0.023	(0.177)	0.461	(1.143)
Gas	-0.074	(-0.112)	0.287	(0.501)	-0.022	(-0.352)	0.318	(2.569**)
Electricity	0.100	(0.803)	0.386	(0.842)	0.048	(0.490)	-0.165	(-1.740*)

Extended energy sub-model

	Coal		Oil		Gas		Electricity	
Coal	-0.167	(-1.133)	0.209	(0.663)	-0.768	(-1.368)	1.616	(6.560**)
Oil	0.130	(0.958)	-0.696	(-3.507**)	-0.003	(0.158)	0.929	(3.621**)
Gas	0.051	(0.419)	0.824	(3.036**)	0.058	(0.007)	0.182	(1.717*)
Electricity	0.200	(1.264)	0.920	(3.542**)	-0.063	(0.001)	-0.252	(-3.847**)

[a] In parentheses, t-statistic is presented.

[b] ** and * means significance at the 5% and 10 % levels, respectively.

Table II-18. Elasticity of Substitution (Japan)

Energy sub-model

	Coal		Oil		Gas		Electricity	
Coal	0.187	(1.973**)	0.160	(1.207)	-0.116	(0.012)	-0.602	(-6.070**)
Oil	-0.151	(-1.264)	-0.020	(-0.525)	-0.287	(-0.587)	-0.120	(-0.915)
Gas	0.116	(2.358**)	0.249	(1.032)	0.330	(0.763)	-0.923	(-2.793**)
Electricity	-0.214	(-2.360**)	0.016	(0.422)	-0.360	(-0.849)	0.061	(5.477**)

Extended energy sub-model

	Coal		Oil		Gas		Electricity	
Coal	0.290	(2.090**)	0.126	(1.548)	0.296	(2.239**)	-0.671	(-4.025**)
Oil	-0.250	(-1.545)	0.029	(0.042)	0.161	(1.790*)	-0.159	(-2.884**)
Gas	-0.047	(0.260)	0.164	(2.057**)	-0.125	(-1.431)	-0.365	(-1.154)
Electricity	-0.321	(-2.289**)	-0.043	(-0.107)	0.116	(1.289)	0.054	(3.743**)

[a] In parentheses, t-statistic is presented.

[b] ** and * means significance at the 5% and 10 % levels, respectively.

Table II-19. Elasticity of Substitution (Korea)

Energy sub-model								
	Coal		**Oil**		**Gas**		**Electricity**	
Coal	0.246	(2.033*)	0.868	(6.165**)	-1.658	(0.878)	0.022	(0.351)
Oil	-0.256	(-2.094**)	-1.068	(-20.67**)	-1.751	(1.260)	1.239	(22.53**)
Gas	0.660	(0.269)	13.029	(6.784**)	1.954	(-1.052)	-14.46	(-11.16**)
Electricity	-0.255	(-2.080**)	1.525	(22.45**)	-2.039	(-0.945)	-0.364	(-21.37**)
Extended energy sub-model								
	Coal		**Oil**		**Gas**		**Electricity**	
Coal	-0.472	(-2.783**)	-1.295	(10.70**)	-6.266	(-0.670)	0.583	(3.696**)
Oil	0.489	(2.896**)	-0.953	(-20.51**)	-6.033	(-0.112)	1.156	(20.66**)
Gas	0.047	(1.323)	8.236	(5.950**)	6.167	(0.315)	-12.67	(-9.473**)
Electricity	0.478	(1.372)	1.372	(22.08**)	-6.238	(-0.421)	-0.354	(-20.04**)

[a] In parentheses, t-statistic is presented.

[b] ** and * means significance at the 5% and 10 % levels, respectively.

Table II-20. Elasticity of Substitution (Netherlands)

Energy sub-model

	Coal		Oil		Gas		Electricity	
Coal	2.035	(6.896**)	2.566	(3.290**)	0.158	(0.971)	-1.323	(-2.473**)
Oil	-1.995	(-6.077**)	-2.357	(-4.862**)	0.952	(2.477**)	2.444	(3.412**)
Gas	-2.056	(-7.115**)	2.495	(5.229**)	-0.562	(-5.283**)	0.962	(4.567**)
Electricity	-2.090	(-6.888**)	2.693	(4.636**)	0.798	(5.397**)	-0.516	(-4.248**)

Extended energy sub-model

	Coal		Oil		Gas		Electricity	
Coal	2.005	(2.628**)	1.412	(2.485**)	-0.430	(-0.606)	-1.287	(-2.729**)
Oil	-2.019	(-2.455**)	-1.481	(-5.072**)	1.513	(5.861**)	0.200	(1.501)
Gas	-2.044	(-2.596**)	1.891	(5.324**)	-0.260	(-4.406**)	-0.152	(-1.855*)
Electricity	-2.042	(-2.676**)	1.536	(4.977**)	0.201	(2.778**)	0.041	(1.193)

[a] In parentheses, t-statistic is presented.

[b] ** and * means significance at the 5% and 10 % levels, respectively.

Table II-21. Elasticity of Substitution (UK)

Energy sub-model

	Coal		Oil		Gas		Electricity	
Coal	2.564	(9.905**)	-0.746	(-1.516)	0.522	(3.910**)	-1.544	(-2.648**)
Oil	-2.849	(-11.94**)	-0.457	(-4.359**)	0.769	(8.850**)	0.313	(1.683)
Gas	-2.505	(-8.901**)	0.737	(6.083**)	-0.333	(-7.540**)	0.001	(0.032)
Electricity	-2.642	(-9.375**)	0.545	(3.997**)	0.331	(5.188**)	-0.007	(-0.089)

Extended energy sub-model

	Coal		Oil		Gas		Electricity	
Coal	2.078	(6.104**)	-1.165	(-4.245**)	0.289	(3.527**)	-0.804	(-1.680)
Oil	-2.375	(-7.164**)	-0.084	(-1.853*)	0.750	(8.958**)	-0.054	(-0.604)
Gas	-2.056	(-5.824**)	0.354	(4.310**)	-0.329	(-7.978**)	0.023	(0.544)
Electricity	-2.104	(-5.829**)	0.079	(1.679)	0.345	(6.417**)	0.014	(0.863)

[a] In parentheses, t-statistic is presented.

[b] ** and * means significance at the 5% and 10 % levels, respectively.

Table II-22. Elasticity of Substitution (US)

Energy sub-model								
	Coal		**Oil**		**Gas**		**Electricity**	
Coal	1.540	(10.76**)	-1.950	(-4.320**)	0.242	(2.057**)	-1.892	(-10.72**)
Oil	-1.686	(-9.825**)	1.484	(4.165**)	-0.495	(-4.072**)	-1.419	(-4.606**)
Gas	-1.494	(-10.94**)	-1.542	(-4.009**)	0.199	(5.055**)	-0.563	(-7.056**)
Electricity	-1.626	(-10.86**)	-1.656	(-4.252**)	-0.317	(-5.754**)	0.376	(6.689**)
Extended energy sub-model								
	Coal		**Oil**		**Gas**		**Electricity**	
Coal	0.489	(0.645)	-1.553	(-4.941**)	0.405	(4.597**)	-1.083	(-2.538**)
Oil	-0.588	(-0.762)	1.243	(5.748**)	-0.478	(-2.765**)	-1.165	(-7.732**)
Gas	-0.427	(-0.484)	-1.297	(-5.168**)	0.194	(3.894**)	-0.507	(-9.072**)
Electricity	-0.532	(-0.728)	-1.378	(-6.166**)	-0.321	(-5.099**)	0.305	(9.526**)

[a] In parentheses, t-statistic is presented.

[b] ** and * means significance at the 5% and 10 % levels, respectively.

6. Discussions and Implications

The Part II analyzes how the investment in the capital asset differentiates the demands of coal, oil, gas, and electricity. Capital assets are classified into six groups: ICT assets; transport equipment; other machinery; other assets; non-residential structures; and residential structures. For the empirical analysis, the energy sub-model (Fuss, 1977) is extended by incorporating a variable regarding the investment in the capital asset. This part analyzes the manufacturing sectors of the ten OECD countries for the derivation of the generalized discussions.

The empirical results show that the capital assets which have the clearest impacts on the demands of the four energy sources are the ICT assets and the transport equipment. The ICT assets increases the demand of electricity while decreases the demands of coal and oil. The transport equipment affects the demands of the four energy sources in an opposite way of the ICT assets. Based on the effect on the electricity demand, this thesis classifies various capital assets into the capital which increases the demand of electricity (EK) and the capital which does not (NK). The ICT assets, other machinery and other assets belong to the EK, and the transport equipment, non-residential structures, and residential structures to the NK.

Further, assumed the above classification of capital assets (EK and NK), the final version of the extended energy-sub model is proposed. The results reveal that the extended model shows generally better performance than the original model. Interfuel substitutability derived by the both models is also compared. Compared to the original model, features of interfuel substitutability are considerably changes in most of the countries. However, a special tendency of changes is not observed. Besides, international comparison of interfuel substitutability gives that the high energy independence, the lower substitutability.

The results of Part II comprehensively show that the incorporation of capital investment into the energy sub-model is appropriate. It is also supported the results of Part I which show that energy and capital are not weakly separable from each other. And these results suggest how to classify various capital assets considering their effects on the demands of different energy sources. If a detailed dataset of the capital assets is available, it will be possible to derive a clearer implication.

PART III. SUBSTITUTABILITY BETWEEN ENERGY AND CAPITAL: APPLICATION OF THE KLEM MODEL

1. Introduction

The uptake of energy-saving technologies is an important means to mitigate greenhouse gas emissions and the depletion of fossil fuels. It can contribute to reducing economy's sensitivity to energy-price fluctuations and to increasing overall efficiency of production. In the context of the producer's theory, the adoption of energy-saving technologies is represented by substitution of capital for energy. That is to say, substitution of capital for energy will permit firms to mitigate the effects of energy price increases by increasing capital investment. In particular, industrial energy demand is a major cause of carbon dioxide emissions and is highly relevant to economic growth. Thus, substitutability between energy and capital in the industrial sector has been continuously an important issue in the energy economics.

Arguments on substitutability between energy and capital began in earnest since the study of Berndt and Wood (1975). They asserted that energy and capital complement each other. In turn, Griffin and Gregory (1976) suggested "the energy-capital hypothesis" of which

the essential point is that there exists substitutability between energy and capital. The hypothesis started from the idea that increases in energy efficiency is achieved through the investment in retrofitting equipment or new engineering designs. Many studies (Berndt and Wood, 1979; Field and Grebenstein, 1980; Fuss, 1977; Garofalo and Malhotra, 1988; Griffin, 1981; Koetse et al., 2008; Prywes, 1986; Thompson and Taylor, 1995) have dealt with this issue intensively. However, no consensus of substitutability between energy and capital has been derived yet.

There are some discussions on reasons of this disagree on substitutability between energy and capital (Berndt and Wood, 1979; Cho et al., 2004; Griffin, 1981; Griffin and Gregory, 1976; Ilmakunnas and Törmä, 1989; Koetse et al., 2008). Putting various ideas suggested by these studies together, one of the main sources of this disagree is the assumption of input factors. For example, Field and Grebenstein (1980) and Garofalo and Malhotra (1988) showed that substitutability between energy and capital is different by capital type. Ilmakunnas and Törmä (1989) and Kim and Heo (2010) showed that substitutability is also different by energy type.

Given that the substitution of capital for energy dominates the substitution of energy for capital, we can say that energy-saving technologies have been adopted through capital investment. This

issue is named as asymmetric substitutability. Only few studies (Feng and Serletis, 2008; Thompson and Taylor, 1995; Welsch and Ochsen, 2005) have discussed asymmetric substitutability. This is because most studies have focused on substitutability itself based on the estimated symmetric elasticity of substitution. The three studies fail to reach agreement, and are not sufficient to generalize asymmetric substitutability between energy and capital.

Asymmetric substitutability is supposed to be related with a producer's decision on the capital investment and the resulted energy consumption. Based on Hartman (1979) explanation, the decision on capital investment precedes the determination of the energy demand, and the substitution of energy for capital may be dominant over. The asymmetry is important, to discuss which policy is appropriate to reduce industrial energy demand.

This study investigates substitutability between energy and capital after 1980, using the data within the manufacturing sectors of the ten OECD countries. The source of disagree on the substitutability between energy and capital, *i.e.*, the assumption of input factors is investigated. Asymmetric substitutability is also examined by employing the Morishima elasticity of substitution. Then, generality and asymmetry of substitutability between energy and capital are discussed.

The remainder of Part III is organized as follows. In the next section, the two issues on substitutability between energy and capital, which has been briefly referred in this section, are described in detail. Then, Section 3 explains the method, focusing on the KLEM model and the measurement of interfactor substitutability. Section 4 introduces the data which consists of cost shares by input, input prices, and output within the manufacturing sector of the ten OECD countries. Subsequently, Section 5 exhibits the empirical results and discusses asymmetric substitutability between energy and capital. Finally, the findings are summarized in Section 6.

2. Two Issues on Substitutability between Energy and Capital

2. 1. Assumption of Input Factors

Since Berndt and Wood (1975) showed the inappropriateness of excluding energy and material from input factors, the assumption of four input factors, i.e., capital (K), labor (L), energy (E), and material (M), has been conventionally applied. Before their study, both energy and capital were regarded as a part of capital input (Paraskevopoulos, 1979). Then, the empirical studies which assume the KLEM, or KLM, or KLE input categorizations have been demonstrated. In this context, how to assume input factors has been briskly discussed.

There exist a series of literatures on the assumption of input factors. They primarily analyze the “nesting structure” among KLEM. For example, if capital and energy are combined with a constant elasticity of substitution, this composite can be regarded as “nested,” and the input factors assumed as (KE)LM. Table III-1 presents an overview of nesting structures which has been assumed in the previous studies. It shows that the assumption of the nesting structure is different by literature. The nesting structure is also different by whether the whole national data is analyzed. Thus, it is hard to apply a certain standard to assume input factors. Kemfert and Welsch

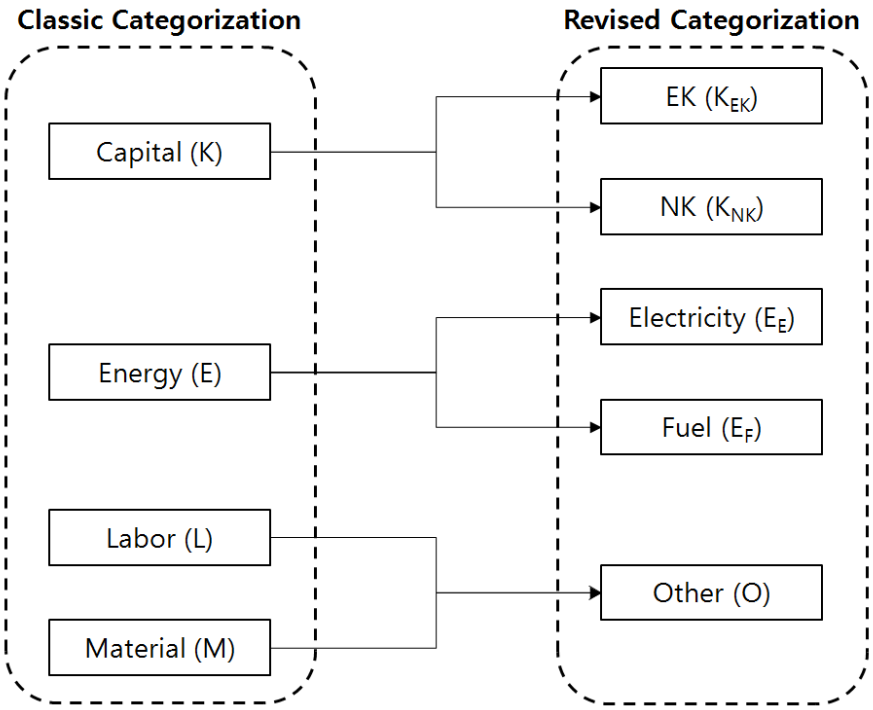
(2000) concluded that the choice of a particular nesting structure is settled by *a priori* reasoning.

Table III-1. Previous Studies on Nesting Structure

Reference	Nesting structure
Manne and Richels (1991)	(KE)L
Burniaux et al. (1992)	(KL)E
Goulder and Schneider (1999)	KLEM
Kemfert and Welsch (2000)	(KE)L
Kemfert (2002)	(KLM)E
Edenhofer et al. (2005)	KLE
van der Werf (2008)	(KL)E

This part assumes five input factors as follows: the capital which increases the electricity demand (EK, K_{EK}); the capital which does not (NK, K_{NK}); electricity (E_E); fuel (E_F); and the aggregate of labor and material (Other, O). The assumption of input factors is based on the results of Part I and Part II. Part I showed that it is better to divide capital and energy into sub-factors in the analysis of the KLEM model because they are not separable from each other. Part II clarified that capital assets can be classified into EK and NK considering their impacts on the electricity demand. This input categorization is different from the original KLEM categorization. Figure III-1 exhibits how the input categorization in this part is different from the original categorization.

Figure III-1. Categorization of Input Factors



Division of energy and capital into sub-inputs is related with the source of systematic variation in the estimation of substitutability between energy and capital. Field and Grebenstein (1980) and Garofalo and Malhotra (1988) showed that substitutability between energy and capital is different by capital type. Ilmakunnas and Törmä (1989) and Kim and Heo (2010) showed that it is also different by energy type. By utilizing the results of the Part II, this part defines the sub-factors of energy and capital, *i.e.*, EK and NK.

The primary reason why labor and material is aggregated into

Other is to analyze substitutability between and energy in depth. As energy is mainly used for operating a variety of capital facilities in the industry sector[19], it is rather related with capital more directly than other factors. Thus, capital is a vehicle that connects energy with labor and material. That is to say, energy exchanges directly impact with capital while it does indirectly with labor and material through capital.

The role of capital as a vehicle in the relationship between energy and labor is supported by some literatures on substitutability between capital and labor (Antony, 2009; Griffin and Gregory, 1976; Nam, 1990; Rowthorn, 1999; Saicheua, 1987). They have agreed that capital tends to substitute labor in developed countries. Following their explanation, capital has substituted labor through the investment on equipment, e.g., automation equipment, which accompanies energy consumption eventually. Moreover, in developed countries, substitutability between energy and capital is caused as the increases in labor price tend to be greater than the increases in capital price (Kim, 2009). Namely, a vehicle which set up substitutability between

[19] Most studies excluded oil and gas used as feedstocks from energy input (reference). Even, some studies regard bituminous coal for iron-making as material not energy (Considine, 1989).

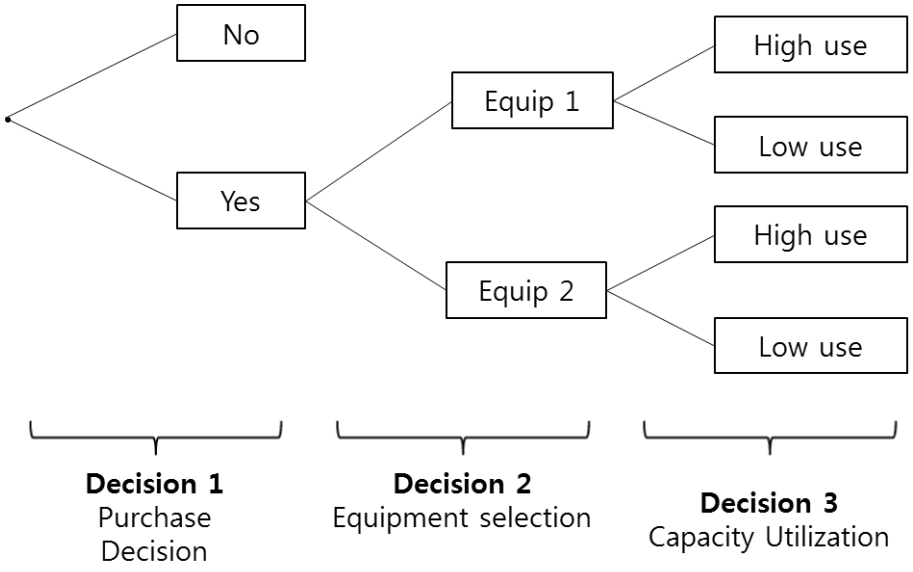
energy and labor is capital. In this context, Berndt and Wood (1979) defined that energy and capital produces the “utilized capital”. Thus, substitutability between energy and labor is rather indirect.

Substitutability between energy and material has been got let attention. Most of the empirical studies of the KLEM model have analyzed it but have not discussed it intensively. However, it is highly possible that substitutability between energy and material is also carried by capital. The amount of material input is determined by both the level of output and the capacity of the facilities. Considering that interfactor substitutability is analyzed with given output, material has a direct relationship with capital investment at the manufacturing sector. Thus, substitutability between energy and material is rather influenced by that between capital and material.

2. 2. Asymmetric Substitutability

To confirm the uptake of energy-saving technologies through capital investment, the direction of substitution should be discussed. If capital substitutes energy, we can say that energy-saving technologies are realized through capital investment. If not, the capital investment does not always guarantee decreases in the energy demand. This issue is connected to the decision making of a producer.

Figure III-2. Three Stages of Energy Demand Behavior



Source: Modification of the Bhattacharryya (2011), p. 45

Hartman (1979) explained that energy demand behavior involves generally three types of decisions on the part of any energy user (demander). The three-stage decision making process is graphically represented in the Figure III-2. First, an agent decides whether to buy or replace a fuel-burning durable good, capable of providing a particular industrial comfort service (e.g. heating, lighting, air conditioning, *etc.*) or industrial process service. Second, he or she decides the technical and economic characteristics of the equipment purchased, he or she decides the type of fuel it uses, and whether the equipment embodies a new technology. Third, given such equipment

and its technical characteristics, he or she decides the frequency and intensity of use. By the energy demand, the decision on the capital investment precedes the determination of the energy demand. In other words, the decision on the energy demand is a kind of by-product of the capital investment.

Further, capital is generally regarded as fixed input in the short run (Morrison, 1988). As the equipment replacement does not frequently occur, the capital demand is not likely to be affected by the changes in energy prices in the short run. Thus, it is expected that substitution of energy for capital is dominant over substitution of capital for energy. In the long run, he it is possible for capital to substitute the energy demand. However, given the energy demand behavior shown in Figure III-2, the direction of substitutability may be ambiguous.

Asymmetric substitutability between energy and capital has been discussed in few literatures. Firstly, Thompson and Taylor (1995) analyzed asymmetric substitutability by utilizing the results of several studies (Anderson, 1981; Berndt and Khaled, 1979; Berndt and Wood, 1975; Denny et al., 1981; Griffin and Gregory, 1976; Hudson and Jorgenson, 1978; Turnovsk et al., 1982; Walton, 1981). They concluded that the substitution of capital for energy is dominant, in the manufacturing sector. Feng and Serletis (2008) also provided

evidences on the predominance of substitution of capital for energy in the US manufacturing from 1950 to 2001. Meanwhile, Welsch and Ochsen (2005) definitely showed that energy substituted capital but capital complemented energy in the manufacturing sector of the West Germany from 1976 to 1994.

The three studies fail to reach an agreement, and are not enough to generalize asymmetric substitutability between energy and capital. Unlike Welsch and Ochsen (2005), Thompson and Taylor (1995) and Feng and Serletis (2008) provided the evidences in the discord with the Hartman's energy demand behavior although These two studies are not enough to refute the energy demand behavior. And, it is hard to consider that they described a normal decision making of a producer as they analyzed the sample covering the two oil shocks in 1970s.

3. Method

3. 1. KLEM Model

The static production structure with n inputs is given by

$$Y = f(x_1, \ldots, x_n, T). \quad \text{(III-1)}$$

$f(\cdot)$ addresses a firm's technology that produces output Y using four input factors, and x_i $(i = 1, \ldots, n)$ denotes i-th input quantity required to produce Y. Here, t represents technical change. If the production function, $f(\cdot)$, is supposed to be twice differentiable, there also exists a twice differentiable cost function corresponding to it. A non-homothetic cost function with non-neutral technical can be written as

$$C = g(p_1, \ldots, p_n, Y, t), \quad \text{(III-2)}$$

where C is the minimum cost required to produce Y, and p_i $(i = 1, \ldots, n)$ is i-th factor price. Also, $g(\cdot)$ is a twice differentiable function. By duality theorem (Shephard, 1953), estimation of Eq. (III-2) can tell all information of a firm's production function as well.

In general, estimation of a corresponding cost function instead of a production function is more preferred especially in case of analyzing the aggregate level data (Binswanger, 1974).

For the estimation, a specific functional for the approximation of C is employed. Particularly, a flexible functional form is needed to impose no *priori* restrictions on elasticities of substitution, *i.e.*, second order approximation of the cost function. A translog function (Christensen et al., 1973), which is the most popular form, is employed in this study. Although a translog approximation tends to move into non-well-behaved regions when the Allen elasticities of substitution move away from unity (Considine, 1989a; Guilkey et al., 1983), it reduces estimation errors in calculating elasticities of substitution because of its simple linearity in logarithms. Due to the popularity of a translog function, it also gives convenience to comparing my result with the results of previous studies.

A translog approximation of a cost function shown in Eq. (III-2) is as follows (Ball and Chambers, 1982);

$$\begin{aligned}\ln C = \alpha_0 + \alpha_Y \ln Y + \sum_{i=1}^{n} \beta_i \ln p_i + \beta_t t + \frac{1}{2}\beta_{YY}(\ln Y)^2 \\ + \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{n}\beta_{ij} \ln p_i \ln p_j + \frac{1}{2}\beta_{TT}T^2 \\ + \sum_{i=1}^{n}\beta_{iY} \ln Y \ln p_i + \sum_{i=1}^{n}\beta_{iT} T \ln p_i\end{aligned} \quad , \qquad \text{(III-3)}$$

where a symmetry condition is imposed by setting $\beta_{ij} = \beta_{ji}$ $(i, j = 1, \ldots, n)$. Because of collinearity problem, estimation of first derivatives of Eq. (III-3) is preferred than the direct estimation of it. By Shephard's lemma (Diewert, 1971), the cost shares associated with Eq. (III-3) are the logarithmic derivatives, and they are defined as

$$S_i(\boldsymbol{p}, Y, T) = \beta_i + \sum_{j=1}^{n} \beta_{ij} \ln p_j + \beta_{iY} \ln Y + \beta_{iT} T \,. \qquad \text{(III-4)}$$

Here, S_i means cost share of i-th $(i = 1, \ldots, n)$ factor. Then, to judge that the approximated production technology is non-homothetic, the hypothesis, $H_0 : \beta_{iY} = 0 \quad \forall i$, is jointly tested. Likewise, to judge its non-neutrality, the hypothesis, $H_0 : \beta_{it} = 0 \quad \forall i$ is also tested. These two tests allow us to determine the final system of cost share equations. To satisfy homogeneity of degree one in prices[20], the following adding-up conditions are imposed on the above equation.

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[20] Homogeneity of degree one in prices does not impose homogeneity of degree one of the production function in inputs.

$$\sum_{i=1}^{n}\beta_i = 1;\ \sum_{i=1}^{n}\beta_{ij} = \sum_{i=1}^{n}\beta_{iY} = \sum_{i=1}^{n}\beta_{iT} = 0. \qquad \text{(III-5)}$$

Due to the adding-up condition, estimation of the system of cost share equations shown in Eq. (III-4) yields singularity. The procedure, therefore, involves dropping one of the equations from the system. Thus, with subtracting a certain input's cost share equation, the system of $n-1$ cost share equations is estimated instead. The parameters of the omitted equation can be recovered using the restrictions Eq. (III-5). If the n-th factor is ruled out, the system of cost share equations are defined as follow.

$$S_i(\boldsymbol{p}, Y, T) = \beta_i + \sum_{j=1}^{n-1}\beta_{ij}\ln\frac{p_j}{p_n} + \beta_{iY}\ln Y + \beta_{iT}T \qquad \text{(III-6)}$$
$$i = 1, \ldots, n-1$$

3. 2. Measurement of Interfactor Substitutability

Two measurements of interfactor substitutability are used in this study: own-price elasticity of substitution η_{ii}; and Morishima elasticity of substitution (MES) σ_{ij}^{m}.

The own-price elasticity measures actual percentage changes in

the i-th input demand from the changes in its own price. If the estimates of η_{ii} is negative, the law of demand is satisfied. In case of translog approximation, it can be calculated as follows:

$$\eta_{ii} = \frac{\beta_{ii}}{S_i} + S_i - 1, \quad if \quad i = j . \tag{III-7}$$

The MES is developed independently by Morishima (1967) and Blackorby and Russell (1989). It is informative when there are more than two inputs. With more than two inputs, interfactor substitutability becomes complex and depends on things like the direction taken towards the point of approximation. The MES between i-th input and j-th input is expressed as

$$\sigma_{ij}^{m} = \eta_{ij} - \eta_{jj} = \frac{\beta_{ij}}{S_i} - \frac{\beta_{jj}}{S_j} + 1, \quad i = 1, \ldots, n . \tag{III-8}$$

The MES measures the percentage changes in the ratio of i-th input to j-th input when the price of j-th inpu alters. If $\sigma_{ij}^{m} > 0$ (that is, if increasing the price of j-th input increases the optimal quantity of i-th input relative to the optimal quantity of j-th input), i-th input will substitute j-th input. If $\sigma_{ij}^{m} < 0$, i-th input will

complement j-th input. The MES can measure the asymmetric substitutability between two inputs. Namely, it allows us to find the main direction of substitutability or complementarity.

4. Data and Descriptive Analysis

4. 1. Data

To estimate the system of cost share equations shown in Eq. (III-6), cost shares and prices of the following five input factors are needed: the capital which increases the electricity demand (EK, K_{EK}); the capital which does not (NK, K_{NK}); electricity (E_E); fuel (E_F); and the aggregate of labor and material (Other, O). This section explains the dataset for the analysis. The manufacturing sectors of the ten OECD countries are analyzed: Australia; Austria; Denmark; Finland; Japan; Korea; Netherlands; UK; and US. Sample period is slightly different by country because of data availability. For Australia, Austria, Denmark, Finland, Italy, Korea, Netherlands, UK, and US, the sample period is from 1980 to 2007 ($T = 28$) and for Japan from 1980 to 2006 ($T = 27$).

Cost shares S_i ($i = K_{EK}, K_{NK}, E_E, E_F, O$) are basically collected from the database of the EU KLEMS consortium. The consortium provides data of compensation for various input factors by industries in the local currency. As the input categorization in this part is different from the existing one, the database of the consortium is properly processed. Then, the costs for the five input factors C_i are

firstly drawn up.

To calculate the costs for the EK and NK, the compensation data for several capital assets (‘capital compensation’) provided by the consortium is used. The consortium provides data of compensation for six capital assets, *i.e.*, the ICT assets, transport equipment, other machinery and equipment, other assets, non-residential structures, and residential structures. Following the discussions in Part II, the ICT assets, other machinery and equipment, and other assets belong to the EK, and the transport equipment, non-residential structures, and residential structures to the NK. That is, the cost for the EK is the summation of compensation for the ICT assets, other machinery and equipment, and other assets. Likewise, the cost for NK is the summation of compensation for the transport equipment, non-residential structures, and residential structures.

The consortium also provides the compensation data for energy. However, it does not give the compensation data for electricity and fuel, respectively. Thus, the cost for electricity is calculated by multiplying electricity price and electricity consumption, which are contained in the *Energy Prices and Taxes* series (IEA, 2011) and the *Energy Balances of OECD Countries* series (IEA, 2011). Subtracting the cost for electricity from the compensation for energy yields the cost for fuel. For the cost data for *Other* , the compensation for labor

and that for material, provided by the consortium, is summed.

Then, the cost shares for the five input factors are calculated, and their sample statistics are described in Table III-2. Some features are observed as follows. The mean EK cost tends to be higher than the mean NK costs. Except Denmark, Finland, and US, the mean electricity cost is higher than the mean fuel cost. In overall, more than 80% of the total cost accounts for *Other* .

Table III-2. Sample Mean Cost Shares for Input Factors

	EK ($S_{K_{EK}}$)	**NK ($S_{K_{NK}}$)**	**Electricity (S_{E_E})**	**Fuel (S_{E_F})**	**Other (S_O)**
Australia	0.068 (0.013)	0.039 (0.009)	0.036 (0.008)	0.025 (0.007)	0.832 (0.018)
Austria	0.069 (0.015)	0.040 (0.009)	0.025 (0.005)	0.011 (0.003)	0.855 (0.017)
Denmark	0.059 (0.010)	0.031 (0.004)	0.024 (0.005)	0.028 (0.016)	0.857 (0.016)
Finland	0.081 (0.015)	0.040 (0.008)	0.032 (0.005)	0.037 (0.020)	0.809 (0.018)
Italy	0.067 (0.005)	0.027 (0.005)	0.044 (0.009)	0.024 (0.014)	0.838 (0.024)
Japan	0.092 (0.012)	0.060 (0.004)	0.022 (0.004)	0.007 (0.003)	0.819 (0.009)
Korea	0.064 (0.007)	0.030 (0.007)	0.058 (0.011)	0.040 (0.017)	0.809 (0.024)
Netherlands	0.063 (0.011)	0.031 (0.004)	0.040 (0.010)	0.032 (0.012)	0.835 (0.016)
UK	0.060 (0.013)	0.028 (0.008)	0.034 (0.008)	0.030 (0.014)	0.848 (0.017)
US	0.073 (0.013)	0.041 (0.007)	0.031 (0.004)	0.034 (0.020)	0.822 (0.012)

[a] Standard deviations are presented in the parenthesis.

Prices p_i $(i = K_{EK}, K_{NK}, E_E, E_F, O)$ are derived by utilizing the dataset of the EU KLEMS consortium, the *Energy Prices and Taxes* series (IEA, 2011) and the *Energy Balances of OECD Countries* series (IEA, 2011). The following two procedures are conducted to derive price indices. First, the prices and quantities of the components of these inputs are prepared. Second, the price indices are calculated using the Divisia index (Diewert, 1976). The Divisia index is used in a variety of official price and productivity statistics, such as the U.S. Bureau of Labor Statistics. Diewert (1974) referred to the Divisia index as a superlative index. This index does not impose a priori restrictions on the degree of substitution between components. Also, it is related to optimizing behavior of the producer (Nguyen, 1987)

To compute the prices of EK, NK, and *Other* , the data from the EU KLEMS consortium are used. To compute the prices of electricity and fuel, the data published by the IEA are used. Table III-3 presents the mean and standard deviation of input prices. All prices are normalized based on 1990=100.

Table III-3. Sample Mean Price Indices of Input Factors (1990=1)

	EK ($S_{K_{EK}}$)	**NK ($S_{K_{NK}}$)**	**Electricity (S_{E_E})**	**Fuel (S_{E_F})**	**Other (S_O)**
Australia	1.124 (0.350)	1.090 (0.426)	1.607 (0.576)	1.703 (0.675)	1.145 (0.337)
Austria	1.307 (0.629)	1.263 (0.599)	0.831 (0.086)	0.917 (0.125)	1.083 (0.177)
Denmark	1.106 (0.251)	1.333 (0.296)	1.285 (0.397)	1.330 (0.645)	1.027 (0.182)
Finland	1.414 (0.574)	1.500 (0.752)	1.682 (0.794)	1.860 (0.848)	1.063 (0.253)
Italy	1.049 (0.242)	1.385 (0.500)	1.320 (0.415)	1.591 (0.694)	1.065 (0.291)
Japan	0.815 (0.191)	0.806 (0.142)	1.041 (0.143)	1.148 (0.313)	0.987 (0.029)
Korea	1.193 (0.377)	2.947 (1.572)	1.590 (0.416)	2.661 (1.857)	1.273 (0.394)
Netherlands	1.061 (0.259)	1.126 (0.450)	1.359 (0.465)	1.342 (0.548)	1.074 (0.179)
UK	0.938 (0.308)	0.871 (0.280)	1.269 (0.278)	1.431 (0.523)	1.051 (0.302)
US	1.054 (0.286)	1.078 (0.434)	0.850 (0.151)	1.171 (0.544)	1.070 (0.204)

[a] Standard deviations are presented in the parenthesis.

4. 2. Correlation Analysis

This part divides capital into EK and NK, and energy into electricity and fuel. This division is based on the effect of various capital assets on the electricity demand. To confirm this division is appropriate, a correlation analysis is carried out. To the analysis, the following variables are defined.

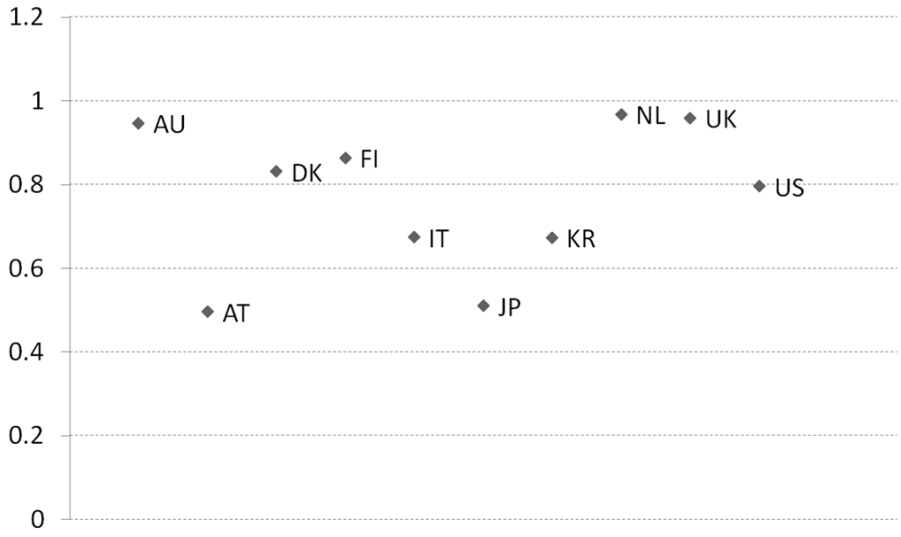
- RK_{EK} = The share of the EK stock to the sum of the EK and NK stocks
- RK_{NK} = The share of the NK stock to the sum of the EK and NK stocks
- RE_E = The share of electricity consumption to the sum of electricity and fuel consumptions
- RE_F = The share of fuel consumption to the sum of electricity and fuel consumptions

RK_{EK} and RK_{NK} denotes the relative stock of EK and that of NK, respectively. RE_E and RE_F separately represents the relative consumption of electricity and that of fuel. The EK stock is derived by the Divisia aggregation of the stocks for the ICT assets, other machinery, and other assets. The NK stock is also calculated by the

same way, *i.e.*, the Divisia aggregation of the stocks for the transport equipment, non-residential structures, and residential structures. The data of these stocks are extracted from the 'real fixed capital stock in 1995 prices' given by the EU KLEMS consortium. The electricity consumption data is gathered from the *Energy Balances of OECD Countries* series (IEA, 2011). The fuel consumption is computed by the Divisia aggregation of the coal, oil, and gas consumptions, which are also collected from the IEA (2011).

Four correlation coefficients are concerned here: correlation coefficient between RK_{EK} and RE_E (r_1); correlation coefficient between RK_{EK} and RE_F (r_2); correlation coefficient between RK_{NK} and RE_E (r_3); and correlation coefficient between RK_{NK} and RE_F (r_4). By construction, r_1 equals r_4, and r_2 does r_3. Also, r_2 has the opposite sign to r_1 but the same absolute value. Thus, an analysis on the correlation coefficient between RK_{EK} and RE_E gives all information we need.

Figure III-3. Correlation Coefficient between RK_{KE} and RE_{E}



AU: Australia, AT: Austria, DK: Denmark, FI: Finland, IT: Italy, JP: Japan, KR: Korea, NL: Netherlands, UK: United Kingdom, US: United States

The correlation coefficient between RK_{EK} and RE_{E} is presented in Figure III-3 by country. In every country analyzed, the correlation coefficient is positive. This result indicates that the higher share of EK stock, the greater electricity consumption while the less fuel consumption. Likewise, the relative increase in the NK stock reduces the electricity consumption while raises the fuel consumption. Therefore, this division of capital and energy into sub-inputs seems to be appropriate from the perspective of energy use.

5. Estimation Results

5. 1. Parameter Estimates

The SUR estimates of the cost function shown in Eq. (III-6) in Table III-4 to III-13, by country. Estimation is performed in the TSP 5.1 package using the LSQ procedure (Hall and Cummins, 2009).

To determine the accurate functional form, both a null hypothesis on a homothetic production technology ($\beta_{iY} = 0, \quad \forall i$) and a null hypothesis on neutral technical change ($\beta_{iT} = 0, \quad \forall i$) is separately tested at the 5% significance level. A log-likelihood ratio (LR) statistic is employed as the test statistic. In Australia, Denmark, Japan, Netherlands, and UK, a cost function dual to a non-homothetic production technology with non-neutral technical change is appropriate. In Austria, Finland, Italy, Korea, and US, a cost function dual to a production technology with non-neutral technical change is appropriate.

The conventional R^2 figure is separately presented for the K_{EK}, K_{NK}, E_E, and E_F equation[21]. In overall, the conventional R^2

[21] Because of singularity, the equation where the dependent variable is the cost share for *Other* (the *O* equation) is excluded from the estimation. Thus, R2 figure

figures, represents the explanatory power of the model, are almost greater than 0.9. It indicates that a translog cost function shown in Eq. (III-6) shows a considerable explanation power for the production structure of the manufacturing sector. However, no R^2 figure greater than 0.9 is observed in the Korean manufacturing. The greatest R^2 figure is 0.9883 for the K_{EK} equation in Australia. The smallest R^2 figure is 0.6374 for the E_E equation in Finland.

The Durbin-Watson Statistic also separately presented for the K_{EK}, K_{NK}, E_E, and E_F equation. It judges the level of serial correlation (Durbin and Watson, 1950, 1951), and will be small for positively autocorrelated and approach 2 for zero correlation. There are few Durbin-Watson statistics close to 2, so the problem of serial correlation occurs in the most of the countries analyzed. It has been typically permitted in case of analyzing the time series data by the KLEM model (Andrikopoulos et al., 1989; Christopoulos, 2000; Considine, 1989b; Considine, 1990; Hall, 1986; Serletis et al., 2010b; Truong, 1985; Urga and Walters, 2003).

A cost function is well-behaved if it is concave in input prices (concavity) and if its input demand functions are strictly positive (monotonicity) (Varian, 1992). Monotonicity requires the fitted cost

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and Durbin-Watson statistic for this equation do not derived.

shares are positive. Concavity requires that a matrix of second partial derivatives of a cost function with respect to prices, *i.e.*, the Hessian matrix, is negative semi-definite. It is also a sufficient condition for negative own-price elasticities (Considine, 1989a).

Monotonicity and concavity violations are checked here (Table III-4 to III-13). The parameter estimates tell that the monotonicity condition is satisfied at all sample points. However, they tell that the concavity condition is not satisfied at the most of the sample points in the every country. Concavity violations imply that this cost function may not be well-behaved. Although, concavity is important for satisfying the duality theorem, concavity violations have been observed many empirical studies applying the KLEM model (Andrikopoulos et al., 1989; Diewert and Wales, 1987; Feng and Serletis, 2008; Harvey and Marshall, 1991; Ryan and Wales, 2000).

Table III-4. Parameter Estimates (Australia)

Parameter	Estimate	p-value	Parameter	Estimate	p-value
$\beta_{K_{EK}}$	2.7833	(0.000)	$\beta_{E_E E_F}$	-0.0021	(0.469)
$\beta_{K_{NK}}$	2.1290	(0.000)	$\beta_{E_E O}$	-0.0182	(0.000)
β_{E_E}	0.1392	(0.816)	$\beta_{E_F E_F}$	0.0216	(0.000)
β_{E_F}	-0.9435	(0.069)	$\beta_{E_F O}$	-0.0162	(0.000)
β_O	-3.1080	(0.001)	β_{OO}	0.0809	(0.000)
$\beta_{K_{EK}K_{EK}}$	0.0512	(0.000)	$\beta_{K_{EK}Y}$	0.0526	(0.000)
$\beta_{K_{EK}K_{NK}}$	-0.0103	(0.000)	$\beta_{K_{NK}Y}$	0.0234	(0.000)
$\beta_{K_{EK}E_E}$	-0.0063	(0.003)	$\beta_{E_E Y}$	0.0172	(0.006)
$\beta_{K_{EK}E_F}$	0.0019	(0.290)	$\beta_{E_F Y}$	-0.0178	(0.001)
$\beta_{K_{EK}O}$	-0.0365	(0.000)	β_{OY}	-0.0755	(0.000)
$\beta_{K_{NK}K_{NK}}$	0.0264	(0.000)	$\beta_{K_{EK}T}$	-0.0014	(0.000)
$\beta_{K_{NK}E_E}$	-0.0008	(0.555)	$\beta_{K_{NK}T}$	-0.0011	(0.000)
$\beta_{K_{NK}E_F}$	-0.0053	(0.000)	$\beta_{E_E T}$	-0.0001	(0.835)
$\beta_{K_{NK}O}$	-0.0100	(0.018)	$\beta_{E_F T}$	0.0005	(0.062)
$\beta_{E_E E_E}$	0.0274	(0.000)	β_{OT}	0.0020	(0.000)
R^2			**Durbin-Watson**		
K_{EK}		0.9883	K_{EK}		2.4204
K_{NK}		0.9693	K_{NK}		1.3924
E_E		0.9457	E_E		0.5151
E_F		0.9833	E_F		1.7860
O		-	O		-
Monotonicity violation		0	**Concavity violation**		19

[a] LR statistic ($\forall\beta_{iY}=0$): 21.026

[b] LR statistic ($\forall\beta_{iT}=0$): 36.660

Table III-5. Parameter Estimates (Austria)

Parameter	Estimate	p-value	Parameter	Estimate	p-value
$\beta_{K_{EK}}$	-1.5343	(0.000)	$\beta_{E_E E_F}$	0.0013	(0.582)
$\beta_{K_{NK}}$	0.3615	(0.000)	$\beta_{E_E O}$	-0.0112	(0.000)
β_{E_E}	0.5100	(0.012)	$\beta_{E_F E_F}$	0.0144	(0.000)
β_{E_F}	0.0789	(0.634)	$\beta_{E_F O}$	-0.0154	(0.000)
β_O	1.5839	(0.000)	β_{OO}	0.0820	(0.000)
$\beta_{K_{EK}K_{EK}}$	0.0357	(0.000)	$\beta_{K_{EK}Y}$	-	-
$\beta_{K_{EK}K_{NK}}$	-0.0037	(0.081)	$\beta_{K_{NK}Y}$	-	-
$\beta_{K_{EK}E_E}$	0.0009	(0.810)	$\beta_{E_E Y}$	-	-
$\beta_{K_{EK}E_F}$	0.0008	(0.788)	$\beta_{E_F Y}$	-	-
$\beta_{K_{EK}O}$	-0.0338	(0.000)	β_{OY}	-	-
$\beta_{K_{NK}K_{NK}}$	0.0284	(0.000)	$\beta_{K_{EK}T}$	0.0008	(0.000)
$\beta_{K_{NK}E_E}$	-0.0019	(0.386)	$\beta_{K_{NK}T}$	-0.0002	(0.001)
$\beta_{K_{NK}E_F}$	-0.0012	(0.437)	$\beta_{E_E T}$	-0.0002	(0.017)
$\beta_{K_{NK}O}$	-0.0216	(0.000)	$\beta_{E_F T}$	-0.0000	(0.692)
$\beta_{E_E E_E}$	0.0109	(0.000)	β_{OT}	-0.0004	(0.018)
R^2			**Durbin-Watson**		
K_{EK}		0.9618	K_{EK}		0.3592
K_{NK}		0.9627	K_{NK}		0.3128
E_E		0.9051	E_E		0.7311
E_F		0.8767	E_F		0.5426
O		-	O		-
Monotonicity violation		0	**Concavity violation**		26

[a] LR statistic ($\forall\beta_{iY}=0$): 7.841

[b] LR statistic ($\forall\beta_{iT}=0$): 20.807

Table III-6. Parameter Estimates (Denmark)

Parameter	Estimate	p-value	Parameter	Estimate	p-value
$\beta_{K_{EK}}$	-0.4705	(0.267)	$\beta_{E_E E_F}$	0.0011	(0.193)
$\beta_{K_{NK}}$	-0.8667	(0.000)	$\beta_{E_E O}$	-0.0191	(0.000)
β_{E_E}	-0.6940	(0.000)	$\beta_{E_F E_F}$	0.0228	(0.000)
β_{E_F}	-0.5693	(0.302)	$\beta_{E_F O}$	-0.0193	(0.000)
β_O	3.6005	(0.000)	β_{OO}	0.0905	(0.000)
$\beta_{K_{EK}K_{EK}}$	0.0364	(0.000)	$\beta_{K_{EK}Y}$	0.0091	(0.120)
$\beta_{K_{EK}K_{NK}}$	-0.0019	(0.217)	$\beta_{K_{NK}Y}$	-0.0069	(0.000)
$\beta_{K_{EK}E_E}$	0.0048	(0.001)	$\beta_{E_E Y}$	-0.0054	(0.001)
$\beta_{K_{EK}E_F}$	-0.0061	(0.000)	$\beta_{E_F Y}$	-0.0204	(0.002)
$\beta_{K_{EK}O}$	-0.0322	(0.000)	β_{OY}	0.0236	(0.034)
$\beta_{K_{NK}K_{NK}}$	0.0245	(0.000)	$\beta_{K_{EK}T}$	0.0003	(0.223)
$\beta_{K_{NK}E_E}$	-0.0043	(0.000)	$\beta_{K_{NK}T}$	0.0005	(0.000)
$\beta_{K_{NK}E_F}$	0.0016	(0.001)	$\beta_{E_E T}$	0.0004	(0.000)
$\beta_{K_{NK}O}$	-0.0199	(0.000)	$\beta_{E_F T}$	0.0003	(0.274)
$\beta_{E_E E_E}$	0.0174	(0.000)	β_{OT}	-0.0014	(0.004)
R^2			**Durbin-Watson**		
K_{EK}		0.9436	K_{EK}		0.6665
K_{NK}		0.9686	K_{NK}		2.1087
E_E		0.9787	E_E		1.4934
E_F		0.9635	E_F		0.7222
O		-	O		-
Monotonicity violation		0	**Concavity violation**		18

[a] LR statistic ($\forall\beta_{iY}=0$): 30.195

[b] LR statistic ($\forall\beta_{iT}=0$): 25.601

Table III-7. Parameter Estimates (Finland)

Parameter	Estimate	p-value	Parameter	Estimate	p-value
$\beta_{K_{EK}}$	-1.6106	(0.000)	$\beta_{E_E E_F}$	-0.0024	(0.596)
$\beta_{K_{NK}}$	0.9162	(0.000)	$\beta_{E_E O}$	0.0047	(0.188)
β_{E_E}	-0.9699	(0.000)	$\beta_{E_F E_F}$	0.0432	(0.000)
β_{E_F}	2.9005	(0.000)	$\beta_{E_F O}$	-0.0276	(0.000)
β_O	-0.2362	(0.529)	β_{OO}	0.0673	(0.000)
$\beta_{K_{EK}K_{EK}}$	0.0529	(0.000)	$\beta_{K_{EK}Y}$	-	-
$\beta_{K_{EK}K_{NK}}$	-0.0087	(0.000)	$\beta_{K_{NK}Y}$	-	-
$\beta_{K_{EK}E_E}$	-0.0077	(0.000)	$\beta_{E_E Y}$	-	-
$\beta_{K_{EK}E_F}$	-0.0103	(0.000)	$\beta_{E_F Y}$	-	-
$\beta_{K_{EK}O}$	-0.0263	(0.000)	β_{OY}	-	-
$\beta_{K_{NK}K_{NK}}$	0.0309	(0.000)	$\beta_{K_{EK}T}$	0.0008	(0.000)
$\beta_{K_{NK}E_E}$	-0.0012	(0.643)	$\beta_{K_{NK}T}$	-0.0004	(0.000)
$\beta_{K_{NK}E_F}$	-0.0029	(0.176)	$\beta_{E_E T}$	0.0005	(0.000)
$\beta_{K_{NK}O}$	-0.0181	(0.000)	$\beta_{E_F T}$	-0.0014	(0.000)
$\beta_{E_E E_E}$	0.0065	(0.315)	β_{OT}	0.0005	(0.005)
R^2			**Durbin-Watson**		
K_{EK}	0.9690		K_{EK}	0.7498	
K_{NK}	0.9238		K_{NK}	0.9067	
E_E	0.6374		E_E	0.9213	
E_F	0.9205		E_F	0.9497	
O	-		O	-	
Monotonicity violation	0		**Concavity violation**	22	

[a] LR statistic ($\forall\beta_{iY}=0$): 1.992

[b] LR statistic ($\forall\beta_{iT}=0$): 16.520

Table III-8. Parameter Estimates (Italy)

Parameter	Estimate	p-value	Parameter	Estimate	p-value
$\beta_{K_{EK}}$	0.5304	(0.000)	$\beta_{E_E E_F}$	0.0015	(0.232)
$\beta_{K_{NK}}$	0.3425	(0.000)	$\beta_{E_E O}$	-0.0297	(0.000)
β_{E_E}	0.6500	(0.000)	$\beta_{E_F E_F}$	0.0318	(0.000)
β_{E_F}	2.5489	(0.000)	$\beta_{E_F O}$	-0.0300	(0.000)
β_O	-3.0719	(0.000)	β_{OO}	0.1030	(0.000)
$\beta_{K_{EK}K_{EK}}$	0.0375	(0.000)	$\beta_{K_{EK}Y}$	-	-
$\beta_{K_{EK}K_{NK}}$	-0.0001	(0.207)	$\beta_{K_{NK}Y}$	-	-
$\beta_{K_{EK}E_E}$	-0.0092	(0.000)	$\beta_{E_E Y}$	-	-
$\beta_{K_{EK}E_F}$	-0.0017	(0.266)	$\beta_{E_F Y}$	-	-
$\beta_{K_{EK}O}$	-0.0256	(0.000)	β_{OY}	-	-
$\beta_{K_{NK}K_{NK}}$	0.0201	(0.000)	$\beta_{K_{EK}T}$	-0.0002	(0.000)
$\beta_{K_{NK}E_E}$	0.0003	(0.575)	$\beta_{K_{NK}T}$	-0.0002	(0.000)
$\beta_{K_{NK}E_F}$	-0.0016	(0.010)	$\beta_{E_E T}$	-0.0003	(0.000)
$\beta_{K_{NK}O}$	-0.0178	(0.000)	$\beta_{E_F T}$	-0.0013	(0.000)
$\beta_{E_E E_E}$	0.0370	(0.000)	β_{OT}	0.0020	(0.000)
R^2			**Durbin-Watson**		
K_{EK}	0.9492		K_{EK}	1.0846	
K_{NK}	0.9626		K_{NK}	1.1148	
E_E	0.9823		E_E	1.0751	
E_F	0.9446		E_F	0.6574	
O	-		O	-	
Monotonicity violation	0		**Concavity violation**	21	

[a] LR statistic ($\forall\beta_{iY}=0$): 12.213

[b] LR statistic ($\forall\beta_{iT}=0$): 31.109

Table III-9. Parameter Estimates (Japan)

Parameter	Estimate	p-value	Parameter	Estimate	p-value
$\beta_{K_{EK}}$	-4.7434	(0.000)	$\beta_{E_E E_F}$	-0.0015	(0.005)
$\beta_{K_{NK}}$	0.0772	(0.671)	$\beta_{E_E O}$	0.0034	(0.530)
β_{E_E}	0.6121	(0.002)	$\beta_{E_F E_F}$	0.0082	(0.000)
β_{E_F}	0.3203	(0.000)	$\beta_{E_F O}$	-0.0039	(0.000)
β_O	4.7338	(0.000)	β_{OO}	0.0551	(0.000)
$\beta_{K_{EK}K_{EK}}$	0.0637	(0.000)	$\beta_{K_{EK}Y}$	0.0195	(0.000)
$\beta_{K_{EK}K_{NK}}$	-0.0191	(0.000)	$\beta_{K_{NK}Y}$	0.0004	(0.901)
$\beta_{K_{EK}E_E}$	-0.0056	(0.050)	$\beta_{E_E Y}$	-0.0137	(0.000)
$\beta_{K_{EK}E_F}$	-0.0028	(0.002)	$\beta_{E_F Y}$	-0.0040	(0.000)
$\beta_{K_{EK}O}$	-0.0361	(0.000)	β_{OY}	-0.0022	(0.701)
$\beta_{K_{NK}K_{NK}}$	0.0424	(0.000)	$\beta_{K_{EK}T}$	0.0024	(0.000)
$\beta_{K_{NK}E_E}$	-0.0047	(0.052)	$\beta_{K_{NK}T}$	-0.0000	(0.947)
$\beta_{K_{NK}E_F}$	-0.0000	(0.996)	$\beta_{E_E T}$	-0.0003	(0.004)
$\beta_{K_{NK}O}$	-0.0185	(0.000)	$\beta_{E_F T}$	-0.0002	(0.000)
$\beta_{E_E E_E}$	0.0084	(0.009)	β_{OT}	-0.0020	(0.000)
R^2			**Durbin-Watson**		
K_{EK}		0.9825	K_{EK}		1.4971
K_{NK}		0.9048	K_{NK}		1.2020
E_E		0.9587	E_E		1.4810
E_F		0.9797	E_F		2.2244
O		-	O		-
Monotonicity violation		0	**Concavity violation**		25

[a] LR statistic ($\forall\beta_{iY}=0$): 86.991

[b] LR statistic ($\forall\beta_{iT}=0$): 45.904

Table III-10. Parameter Estimates (Korea)

Parameter	Estimate	p-value	Parameter	Estimate	p-value
$\beta_{K_{EK}}$	-1.7644	(0.000)	$\beta_{E_E E_F}$	0.0004	(0.903)
$\beta_{K_{NK}}$	-0.0386	(0.724)	$\beta_{E_E O}$	-0.0561	(0.000)
β_{E_E}	-0.9907	(0.000)	$\beta_{E_F E_F}$	0.0265	(0.000)
β_{E_F}	3.3542	(0.000)	$\beta_{E_F O}$	-0.0126	(0.003)
β_O	0.4395	(0.565)	β_{OO}	0.1127	(0.000)
$\beta_{K_{EK}K_{EK}}$	0.0423	(0.000)	$\beta_{K_{EK}Y}$		
$\beta_{K_{EK}K_{NK}}$	-0.0040	(0.000)	$\beta_{K_{NK}Y}$		
$\beta_{K_{EK}E_E}$	0.0055	(0.030)	$\beta_{E_E Y}$		
$\beta_{K_{EK}E_F}$	-0.0096	(0.000)	$\beta_{E_F Y}$		
$\beta_{K_{EK}O}$	-0.0342	(0.000)	β_{OY}		
$\beta_{K_{NK}K_{NK}}$	0.0194	(0.000)	$\beta_{K_{EK}T}$	0.0009	(0.000)
$\beta_{K_{NK}E_E}$	-0.0010	(0.432)	$\beta_{K_{NK}T}$	0.0000	(0.601)
$\beta_{K_{NK}E_F}$	-0.0046	(0.000)	$\beta_{E_E T}$	0.0005	(0.000)
$\beta_{K_{NK}O}$	-0.0098	(0.000)	$\beta_{E_F T}$	-0.0017	(0.000)
$\beta_{E_E E_E}$	0.0513	(0.000)	β_{OT}	0.0002	(0.605)
R^2			**Durbin-Watson**		
K_{EK}	0.7528		K_{EK}	0.3425	
K_{NK}	0.8259		K_{NK}	0.8322	
E_E	0.8379		E_E	0.3178	
E_F	0.8369		E_F	0.2028	
O	-		O	-	
Monotonicity violation	0		**Concavity violation**	12	

[a] LR statistic ($\forall\beta_{iY}=0$): 3.713

[b] LR statistic ($\forall\beta_{iT}=0$): 17.913

Table III-11. Parameter Estimates (Netherlands)

Parameter	Estimate	p-value	Parameter	Estimate	p-value
$\beta_{K_{EK}}$	4.5270	(0.000)	$\beta_{E_E E_F}$	-0.0009	(0.400)
$\beta_{K_{NK}}$	1.5581	(0.005)	$\beta_{E_E O}$	-0.0300	(0.000)
β_{E_E}	0.4632	(0.453)	$\beta_{E_F E_F}$	0.0342	(0.000)
β_{E_F}	-1.3492	(0.289)	$\beta_{E_F O}$	-0.0287	(0.000)
β_O	-4.1989	(0.056)	β_{OO}	0.0931	(0.000)
$\beta_{K_{EK}K_{EK}}$	0.0272	(0.000)	$\beta_{K_{EK}Y}$	0.0882	(0.000)
$\beta_{K_{EK}K_{NK}}$	-0.0036	(0.006)	$\beta_{K_{NK}Y}$	0.0113	(0.150)
$\beta_{K_{EK}E_E}$	-0.0037	(0.012)	$\beta_{E_E Y}$	0.0129	(0.149)
$\beta_{K_{EK}E_F}$	-0.0069	(0.000)	$\beta_{E_F Y}$	-0.0469	(0.008)
$\beta_{K_{EK}O}$	-0.0129	(0.019)	β_{OY}	-0.0656	(0.036)
$\beta_{K_{NK}K_{NK}}$	0.0264	(0.000)	$\beta_{K_{EK}T}$	-0.0023	(0.000)
$\beta_{K_{NK}E_E}$	-0.0036	(0.000)	$\beta_{K_{NK}T}$	-0.0008	(0.006)
$\beta_{K_{NK}E_F}$	0.0023	(0.041)	$\beta_{E_E T}$	-0.0002	(0.482)
$\beta_{K_{NK}O}$	-0.0215	(0.000)	$\beta_{E_F T}$	0.0007	(0.275)
$\beta_{E_E E_E}$	0.0382	(0.000)	β_{OT}	0.0025	(0.022)
R^2			**Durbin-Watson**		
K_{EK}		0.9742	K_{EK}		1.0050
K_{NK}		0.9315	K_{NK}		0.4730
E_E		0.9853	E_E		0.8956
E_F		0.9587	E_F		2.2214
O		-	O		-
Monotonicity violation		0	**Concavity violation**		23

[a] LR statistic ($\forall\beta_{iY}=0$): 19.900

[b] LR statistic ($\forall\beta_{iT}=0$): 33.114

Table III-12. Parameter Estimates (UK)

Parameter	Estimate	p-value	Parameter	Estimate	p-value
$\beta_{K_{EK}}$	0.2236	(0.560)	$\beta_{E_E E_F}$	0.0014	(0.389)
$\beta_{K_{NK}}$	-1.0070	(0.000)	$\beta_{E_E O}$	-0.0241	(0.000)
β_{E_E}	0.4956	(0.277)	$\beta_{E_F E_F}$	0.0266	(0.000)
β_{E_F}	-0.4863	(0.271)	$\beta_{E_F O}$	-0.0277	(0.000)
β_O	1.7741	(0.002)	β_{OO}	0.1111	(0.000)
$\beta_{K_{EK}K_{EK}}$	0.0450	(0.000)	$\beta_{K_{EK}Y}$	0.0192	(0.001)
$\beta_{K_{EK}K_{NK}}$	-0.0003	(0.825)	$\beta_{K_{NK}Y}$	-0.0172	(0.000)
$\beta_{K_{EK}E_E}$	-0.0082	(0.000)	$\beta_{E_E Y}$	0.0211	(0.000)
$\beta_{K_{EK}E_F}$	0.0004	(0.761)	$\beta_{E_F Y}$	-0.0172	(0.004)
$\beta_{K_{EK}O}$	-0.0369	(0.000)	β_{OY}	-0.0059	(0.477)
$\beta_{K_{NK}K_{NK}}$	0.0276	(0.000)	$\beta_{K_{EK}T}$	-0.0001	(0.663)
$\beta_{K_{NK}E_E}$	-0.0042	(0.001)	$\beta_{K_{NK}T}$	0.0005	(0.000)
$\beta_{K_{NK}E_F}$	-0.0007	(0.514)	$\beta_{E_E T}$	-0.0002	(0.291)
$\beta_{K_{NK}O}$	-0.0224	(0.000)	$\beta_{E_F T}$	0.0003	(0.244)
$\beta_{E_E E_E}$	0.0352	(0.000)	β_{OT}	-0.0005	(0.118)
R^2			**Durbin-Watson**		
K_{EK}		0.9858	K_{EK}		1.3269
K_{NK}		0.9821	K_{NK}		1.7558
E_E		0.9782	E_E		0.8746
E_F		0.9848	E_F		1.3004
O		-	O		-
Monotonicity violation		0	**Concavity violation**		26

[a] LR statistic ($\forall\beta_{iY}=0$): 22.764

[b] LR statistic ($\forall\beta_{iT}=0$): 63.107

Table III-13. Parameter Estimates (US)

Parameter	Estimate	p-value	Parameter	Estimate	p-value
$\beta_{K_{EK}}$	-2.2454	(0.000)	$\beta_{E_E E_F}$	-0.0050	(0.000)
$\beta_{K_{NK}}$	0.2575	(0.097)	$\beta_{E_E O}$	-0.0309	(0.000)
β_{E_E}	0.0633	(0.679)	$\beta_{E_F E_F}$	0.0443	(0.000)
β_{E_F}	2.7919	(0.000)	$\beta_{E_F O}$	-0.0392	(0.000)
β_O	0.1327	(0.710)	β_{OO}	0.1322	(0.000)
$\beta_{K_{EK}K_{EK}}$	0.0552	(0.000)	$\beta_{K_{EK}Y}$		
$\beta_{K_{EK}K_{NK}}$	-0.0131	(0.000)	$\beta_{K_{NK}Y}$		
$\beta_{K_{EK}E_E}$	-0.0041	(0.035)	$\beta_{E_E Y}$		
$\beta_{K_{EK}E_F}$	0.0002	(0.773)	$\beta_{E_F Y}$		
$\beta_{K_{EK}O}$	-0.0382	(0.000)	β_{OY}		
$\beta_{K_{NK}K_{NK}}$	0.0356	(0.000)	$\beta_{K_{EK}T}$	0.0012	(0.000)
$\beta_{K_{NK}E_E}$	0.0018	(0.393)	$\beta_{K_{NK}T}$	-0.0001	(0.167)
$\beta_{K_{NK}E_F}$	-0.0003	(0.651)	$\beta_{E_E T}$	-0.0000	(0.878)
$\beta_{K_{NK}O}$	-0.0240	(0.000)	$\beta_{E_F T}$	-0.0014	(0.000)
$\beta_{E_E E_E}$	0.0383	(0.000)	β_{OT}	0.0003	(0.056)
R^2			**Durbin-Watson**		
K_{EK}		0.9898	K_{EK}		1.4950
K_{NK}		0.9594	K_{NK}		0.5962
E_E		0.8753	E_E		0.9655
E_F		0.9350	E_F		0.7728
O		-	O		-
Monotonicity violation		0	**Concavity violation**		28

[a] LR statistic ($\forall\beta_{iY}=0$): 9.993

[b] LR statistic ($\forall\beta_{iT}=0$): 14.966

5. 2. Interfactor Substitutability

To measure interfactor substitutability, I estimate own-price elasticities η_{ii} and the Morishima elasticities of substitution (MES) σ_{ij}^{m} using the parameter estimates of Eq. (4). Their estimates are demonstrated in Tables III-14 to 23 by country. In the diagonal terms, own-price elasticities calculated by Eq. (6) are described, while the MES calculated by Eq. (7) are described in the off-diagonal terms. The mean and t-statistic of the elasticity are estimated by the delta method (Greene, 2002). Several important results emerge from the estimates of own-price elasticities and the MESs.

First, in general, the most price-responsive input is EK, capital that increases electricity demand. The magnitude of the own-price elasticities for EK is the smallest among the five inputs within the manufacturing sectors of Australia, Denmark, Italy, Korea, the Netherlands, the UK, and the US. In Austria and Finland, the own-price elasticity for EK is the second smallest. In addition, the sign of the own-price elasticities for EK are significantly negative in every country analyzed. Thus, it is likely that the increases in the EK price always yield decreases in its own demand. This means that the manufacturing sector responds rather sensitively to changes in the EK

price.

Second, in general, the least price-responsive input is fuel. The own-price elasticities for fuel are the greatest—and all positive—except for the UK. Even in the UK, it is the second largest, and positive as well. These results indicate that fuel demand increases even though its price increases. That is, the law of demand is not satisfied in fuel demand. Thus, the manufacturing sectors do not respond that sensitively to price changes of coal, oil, and gas.

Third, most estimates of $\sigma^m_{E_E-K_{EK}}$ and $\sigma^m_{E_F-K_{EK}}$ are so positive that fuel as well as electricity tend to substitute for EK in case of increases in the EK price. There are exceptions: the estimates of $\sigma^m_{E_F-K_{EK}}$ in Finland and Japan are, respectively, -0.0117 and -0.1279, but they are not statistically significant at the 10% level. Likewise, $\sigma^m_{E_E-K_{EK}}$ of the UK is estimated to be -0.0338, which is also not significant. Therefore, both electricity and fuel tend to substitute for EK.

Fourth, the positive estimates of $\sigma^m_{K_{EK}-E_E}$ $\sigma^m_{K_{NK}-E_E}$ in Australia, Austria, Denmark, Finland, Japan, and Korea indicate that both EK and NK substitute for electricity in these countries. In Italy, although $\sigma^m_{K_{EK}-E_E}$ is estimated to be -0.0182, it is not statistically significant.

Thus, the demands of two capital inputs substitute for electricity in Australia, Denmark, Finland, Italy, Japan, and Korea. However, estimates of $\sigma^m_{K_{EK}-E_E}$ and $\sigma^m_{K_{NK}-E_E}$ are both negative in the Netherlands, the UK, and the US: capital inputs do not substitute for electricity. In sum, the response of capital demand to increases in the electricity price differs by country.

Fifth, all estimates of $\sigma^m_{K_{EK}-E_F}$ and $\sigma^m_{K_{NK}-E_F}$ are negative in Austria, Finland, Italy, Japan, the Netherlands, the UK, and the US. This indicates that both EK and NK complement fuel in these countries. However, in Korea, the estimates of $\sigma^m_{K_{EK}-E_F}$ and $\sigma^m_{K_{NK}-E_F}$ are positive such that both EK and NK substitute for fuel. In Australia and Denmark, the response to the changes of fuel prices differs by capital type.

Sixth, the significant estimates σ^m_{i-O} ($i = K_{EK}, K_{NK}, E_E, E_F$) are positive except for Austria, Italy, and the US, where the estimates of $\sigma^m_{E_F-O}$ are significantly negative. That is, when the price of *Other* changes, most input factors tend to substitute for *Other*. Given that the cost share for *Other* is over 80% in all 10 countries, the tendency of substitution of *Other* by other inputs corresponds to our expectation.

Seventh, the absolute values of most estimates of elasticities are smaller than 1, which means that the demand for inputs shows inelastic responses to their price. There are exceptions: the estimates of $\sigma^{m}_{E_E-O}$ in Finland and Japan are greater than 1 such that the responses of electricity demand are elastic to the *Other* price. That is, demand changes induced by input price changes are not great in almost every country.

In sum, energy inputs generally substitute capital inputs but capital inputs do not substitute energy inputs. Especially, both EK and NK complement fuel. *Other* for which the cost share is the greatest among input factors is in a substitution relationship with other inputs except fuel. The relationship between capital and other input factors is not different by capital type. However, the relationship between energy and other input factors is different by energy type. Thus, the separation of electricity and fuel is a major source of systematic variation in substitutability between energy and capital.

Table III-14. Elasticity of Substitution (Australia)

	K_{EK}		K_{NK}		E_E		E_F		O	
K_{EK}	-0.4790	(-4.199**)	0.1105	(2.237**)	0.0946	(1.881*)	0.1194	(1.158)	0.3445	(5.676**)
K_{NK}	-0.0683	(-0.225)	-0.2288	(-3.897**)	0.1698	(2.505**)	-0.0575	(-0.088)	0.6249	(5.390**)
E_E	0.0298	(1.056)	0.2446	(3.694**)	-0.1557	(-2.611**)	0.0291	(0.298)	0.3655	(3.475**)
E_F	0.2989	(2.651**)	0.0445	(1.286)	0.1051	(0.730)	-0.0644	(-0.907)	0.2204	(2.060**)
O	0.1733	(4.504**)	0.2557	(4.024**)	0.1697	(2.732**)	0.0702	(0.956)	-0.0710	(-5.625**)

[a] Numbers in parentheses are t-statistics; b ***, **, and * mean that the estimate is statistically significant at the 1%, 5%, and 10% level, respectively.

Table III-15. Elasticity of Substitution (Austria)

	K_{EK}		K_{NK}		E_E		E_F		O	
K_{EK}	-0.3873	(-6.017**)	0.2040	(4.297**)	0.5493	(6.023**)	-0.4687	(-1.532)	0.3892	(5.395**)
K_{NK}	0.3612	(3.789**)	-0.2193	(-7.365**)	0.4848	(3.102**)	-0.5121	(-2.142**)	0.3401	(5.743**)
E_E	0.4948	(4.049**)	0.1774	(1.514)	-0.5109	(-4.655**)	-0.4285	(-1.136)	0.4303	(4.734**)
E_F	0.5455	(1.432)	0.1389	(0.762)	0.6661	(2.048**)	0.4923	(1.831*)	-0.6765	(-2.382**)
O	0.4169	(6.021**)	0.2343	(7.742**)	0.5224	(4.681**)	-0.4996	(-1.871*)	-0.0488	(-6.607**)

[a] Numbers in parentheses are t-statistics; b ***, **, and * mean that the estimate is statistically significant at the 1%, 5%, and 10% level, respectively.

Table III-16. Elasticity of Substitution (Denmark)

	K_{EK}		K_{NK}		E_E		E_F		O	
K_{EK}	-0.3248	(-4.340**)	0.1680	(3.202**)	0.3403	(7.497**)	-0.0869	(0.891)	0.3338	(3.992**)
K_{NK}	0.3219	(3.203**)	-0.1700	(-5.319**)	0.1163	(2.247**)	0.0707	(3.427**)	0.2464	(6.066**)
E_E	0.5911	(6.837**)	0.0180	(0.725)	-0.2317	(-4.035**)	0.0665	(2.327**)	0.0797	(1.121)
E_F	0.1209	(1.225)	0.2688	(6.509**)	0.3032	(3.411**)	0.0087	(-2.815**)	0.0624	(2.442**)
O	0.3465	(4.339**)	0.1780	(5.587**)	0.2337	(3.924**)	-0.0030	(2.827**)	-0.0374	(-4.670**)

[a] Numbers in parentheses are t-statistics; b ***, **, and * mean that the estimate is statistically significant at the 1%, 5%, and 10% level, respectively.

Table III-17. Elasticity of Substitution (Finland)

	K_{EK}		K_{NK}		E_E		E_F		O	
K_{EK}	-0.2419	(-13.189**)	0.0899	(2.167**)	0.6950	(3.344**)	-0.5379	(-2.315**)	0.5809	(15.209**)
K_{NK}	0.0980	(3.166**)	-0.1608	(-3.317**)	0.7631	(3.661**)	-0.4815	(-1.958*)	0.4482	(4.859**)
E_E	0.0802	(1.688)	0.1645	(2.561**)	-0.7607	(-3.790**)	-0.4822	(-1.460)	1.0652	(9.013**)
E_F	-0.0117	(0.217)	0.1065	(1.113)	0.7151	(2.087**)	0.4436	(1.615)	0.0178	(2.129**)
O	0.2908	(14.266**)	0.1787	(3.408**)	0.7987	(3.937**)	-0.4404	(-1.513)	-0.1078	(-11.794**)

[a] Numbers in parentheses are t-statistics; b ***, **, and * mean that the estimate is statistically significant at the 1%, 5%, and 10% level, respectively.

Table III-18. Elasticity of Substitution (Italy)

	K_{EK}		K_{NK}		E_E		E_F		O	
K_{EK}	-0.3680	(-11.941**)	0.2184	(12.123**)	-0.0182	(0.244)	-0.6388	(-4.173**)	0.4907	(10.748**)
K_{NK}	0.3968	(11.458**)	-0.2062	(-8.313**)	0.1320	(3.283**)	-0.6749	(-4.565**)	0.1983	(3.606**)
E_E	0.2158	(5.595**)	0.2402	(10.969**)	-0.0771	(-2.637**)	-0.5770	(-3.398**)	0.1731	(3.380**)
E_F	0.3499	(4.193**)	0.1519	(3.526**)	0.1993	(2.632**)	0.6379	(4.274**)	-0.6491	(-3.269**)
O	0.4041	(11.932**)	0.2121	(8.026**)	0.0855	(2.693**)	-0.6496	(-4.328**)	-0.0387	(-5.951**)

[a] Numbers in parentheses are t-statistics; b ***, **, and * mean that the estimate is statistically significant at the 1%, 5%, and 10% level, respectively.

Table III-19. Elasticity of Substitution (Japan)

	K_{EK}		K_{NK}		E_E		E_F		O	
K_{EK}	-0.2034	(-6.424**)	0.0783	(1.300)	0.5384	(4.131**)	-0.2579	(-3.017**)	0.5334	(8.862**)
K_{NK}	-0.0247	(-0.286)	-0.2297	(-4.610**)	0.5218	(3.606**)	-0.2265	(-2.387**)	0.6217	(10.521**)
E_E	0.0283	(0.131)	0.0664	(0.518)	-0.5790	(-3.966**)	-0.2977	(-3.255**)	1.0952	(4.187**)
E_F	-0.1279	(-0.832)	0.2890	(2.078**)	0.3773	(2.231**)	0.2338	(2.485**)	0.3537	(3.407**)
O	0.2516	(6.975**)	0.2670	(5.123**)	0.6048	(3.968**)	-0.2311	(-2.410**)	-0.1140	(-10.246**)

[a] Numbers in parentheses are t-statistics; b ***, **, and * mean that the estimate is statistically significant at the 1%, 5%, and 10% level, respectively.

Table III-20. Elasticity of Substitution (Korea)

	K_{EK}		K_{NK}		E_E		E_F		O	
K_{EK}	-0.2647	(-8.856**)	0.2586	(6.158**)	0.1586	(1.659)	0.0908	(3.270**)	0.3183	(5.592**)
K_{NK}	0.1881	(4.059**)	-0.2922	(-6.579**)	0.0358	(0.638)	0.0828	(1.886*)	0.5196	(10.875**)
E_E	0.4282	(9.207**)	0.3040	(4.841**)	-0.0136	(-0.576)	0.2505	(3.743**)	-0.1563	(-1.606)
E_F	0.0535	(1.136)	0.1908	(3.645**)	0.0819	(0.788)	-0.2039	(-5.626**)	0.5002	(4.610**)
O	0.2861	(8.776**)	0.3104	(6.820**)	0.0018	(0.446)	0.2281	(5.795**)	-0.0519	(-4.472**)

[a] Numbers in parentheses are t-statistics; b ***, **, and * mean that the estimate is statistically significant at the 1%, 5%, and 10% level, respectively.

Table III-21. Elasticity of Substitution (Netherlands)

	K_{EK}		K_{NK}		E_E		E_F		O	
K_{EK}	-0.4864	(-8.754**)	0.0593	(1.959*)	-0.0704	(-1.385)	-0.3466	(-2.911**)	0.6741	(6.718**)
K_{NK}	0.4282	(9.862**)	-0.0889	(-3.304**)	-0.1231	(-3.304**)	-0.1554	(-0.508)	0.1715	(1.901*)
E_E	0.4508	(9.958**)	0.0248	(1.032)	0.0490	(-0.298)	-0.2567	(-1.374)	0.0974	(1.682)
E_F	0.3001	(3.158**)	0.2022	(3.446**)	-0.0424	(0.521)	0.2635	(1.551)	-0.1436	(-0.211)
O	0.5336	(8.634**)	0.0936	(2.746**)	-0.0446	(0.353)	-0.2663	(-1.543)	-0.0535	(-3.806**)

[a] Numbers in parentheses are t-statistics; b ***, **, and * mean that the estimate is statistically significant at the 1%, 5%, and 10% level, respectively.

Table III-22. Elasticity of Substitution (UK)

	K_{EK}		K_{NK}		E_E		E_F		O	
K_{EK}	-0.1610	(-6.142**)	-0.1027	(-0.447)	-0.2329	(-2.738**)	-0.0758	(1.313)	0.2311	(5.793**)
K_{NK}	0.2111	(4.176**)	0.1260	(0.690)	-0.2586	(-2.590**)	-0.1100	(0.339)	-0.0228	(0.792)
E_E	-0.0338	(-0.506)	-0.2294	(-2.588**)	0.1243	(1.196)	-0.0396	(1.107)	0.1225	(1.833)
E_F	0.2358	(3.489**)	-0.1269	(-1.091)	-0.0346	(0.328)	0.1122	(-1.158)	-0.2545	(-0.754)
O	0.1778	(6.365**)	-0.1248	(-0.622)	-0.1187	(-1.070)	-0.1146	(1.147)	-0.0212	(-2.782**)

[a] Numbers in parentheses are t-statistics; b ***, **, and * mean that the estimate is statistically significant at the 1%, 5%, and 10% level, respectively.

Table III-23. Elasticity of Substitution (US)

	K_{EK}		K_{NK}		E_E		E_F		O	
K_{EK}	-0.1448	(-3.321**)	-0.0878	(-0.673)	-0.3130	(-2.302**)	-0.7484	(-3.830**)	0.2979	(6.317**)
K_{NK}	-0.1143	(-0.853)	-0.0575	(-1.244)	-0.2086	(-1.307)	-0.7600	(-4.023**)	0.2318	(3.602**)
E_E	0.0829	(1.028)	0.1577	(1.359)	0.2857	(2.254**)	-0.9164	(-5.651**)	-0.1754	(-1.632)
E_F	0.2263	(5.036**)	0.0848	(2.092**)	-0.4533	(-3.147**)	0.7852	(4.305**)	-0.7091	(-4.010**)
O	0.1713	(3.643**)	0.0689	(1.408)	-0.2923	(-2.264**)	-0.7992	(-4.319**)	-0.0174	(-2.640**)

[a] Numbers in parentheses are t-statistics; b ***, **, and * mean that the estimate is statistically significant at the 1%, 5%, and 10% level, respectively.

5. 3. Asymmetric Substitutability between Energy and Capital

The MES estimates indicate that since 1980, energy tends to substitute for capital but capital does not substitute for energy, especially fuel, within the manufacturing sectors of the analyzed countries. That is, asymmetric substitutability between energy and capital is observed. To check this asymmetry more clearly, the MES estimates between energy inputs and capital inputs are presented in Figures III-4~III-6 [22]. Asymmetry is remarkable between EK and fuel and between NK and fuel. Fuel substitutes for both EK and NK, but they seem to complement fuel. This asymmetry is hard to be captured when neither energy nor capital is divided input sub-inputs (See Appendix III).

[22] AU: Australia, AT: Austria, DK: Denmark, FI: Finland, IT: Italy, JP: Japan, KR: Korea, NL: Netherlands, UK: United Kingdom, US: United States

Figure III-4. MES between EK and Electricity

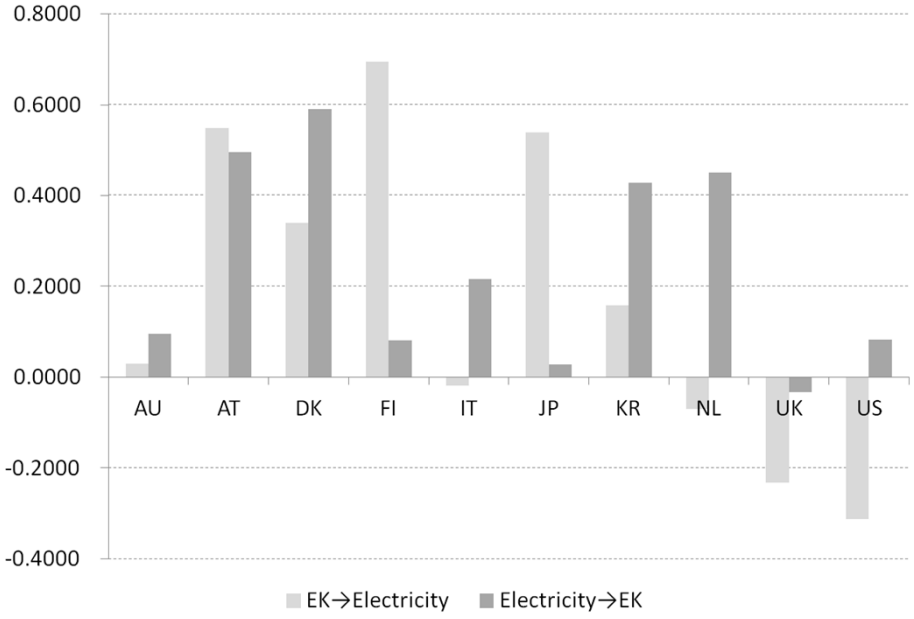


Figure III-5. MES between EK and Fuel

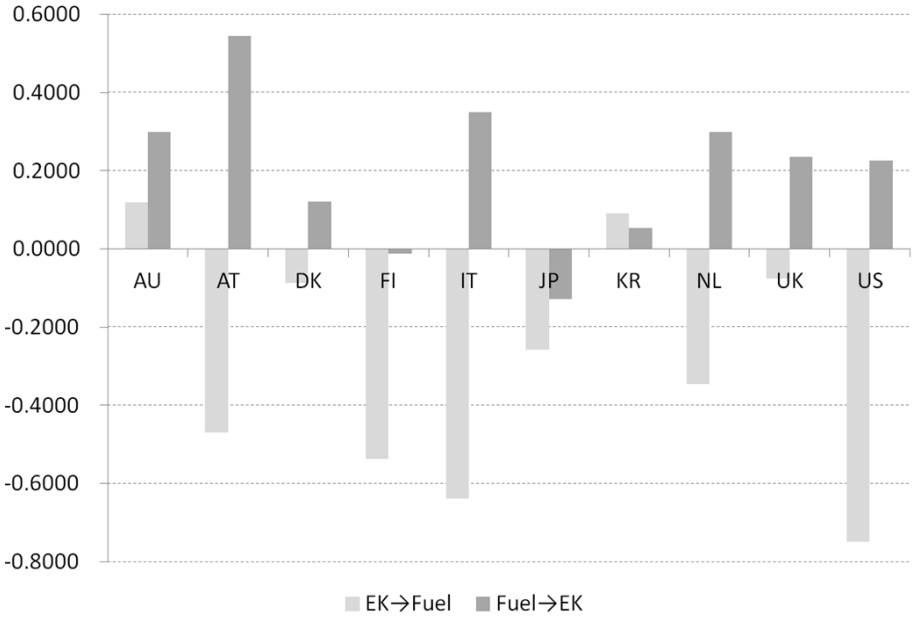


Figure III-6. MES between NK and Electricity

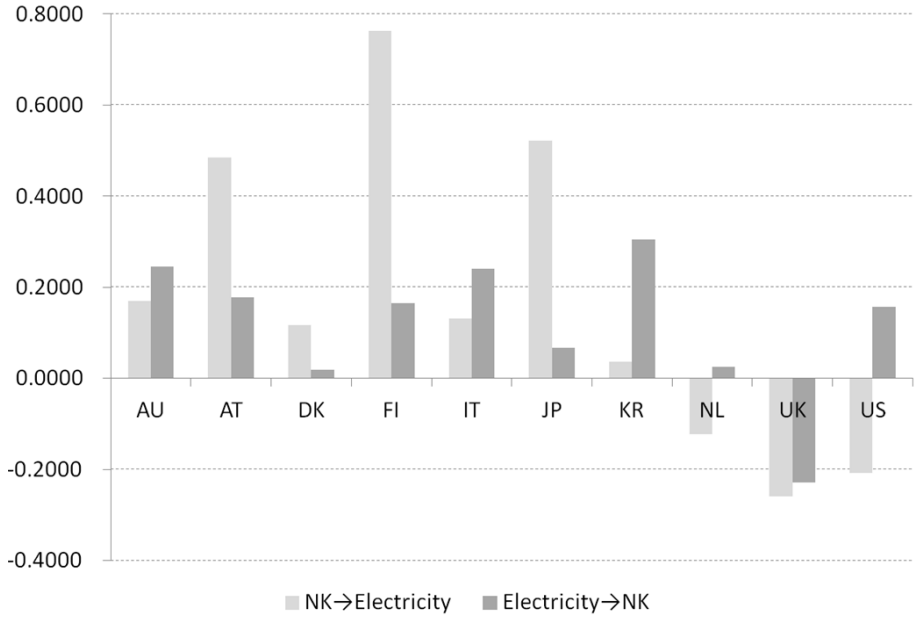
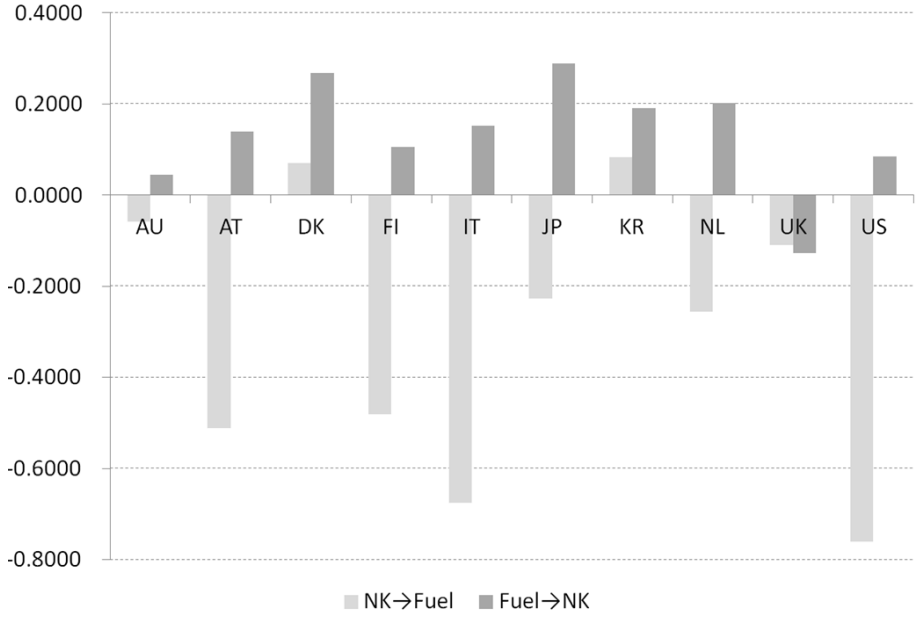


Figure III-7. MES between NK and Fuel

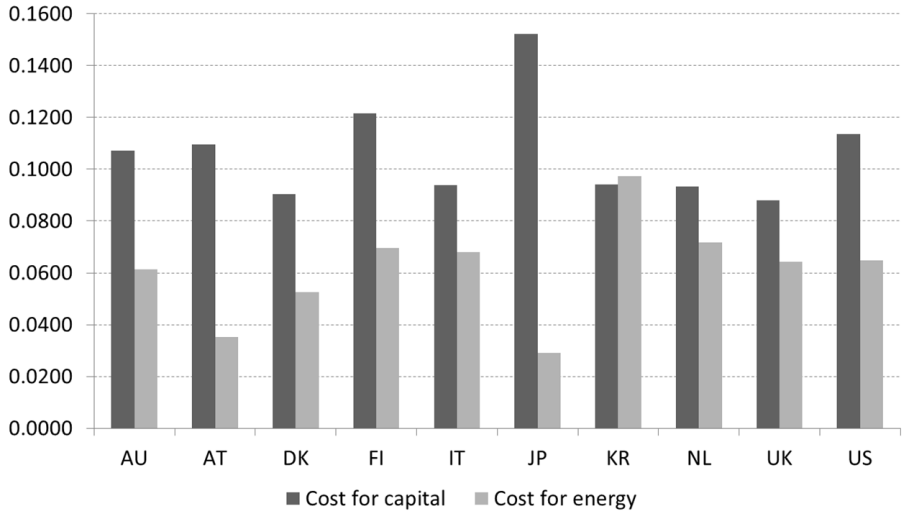


This asymmetric substitutability between energy and capital is contrary to the results of Thompson and Taylor (1995) and Feng and Serletis (2008). This disagreement is likely related to whether the period with oil shocks is included in the sample period. Both the two studies include the oil shock period, but this study does not. Meanwhile, Feng and Serletis (2008) and Ilmakunnas and Törmä (1989) showed that the substitution of energy for capital is considerably mitigated if the oil shock period is excluded from the sample. The results of Welsch and Ochsen (2005) which analyzed interfactor substitutability in the manufacturing sector of West Germany after the oil shocks are in accordance with this study.

The asymmetric substitutability between energy and capital can be explained by the energy demand behavior (Hartman, 1979). Following his discussion, the energy demand behavior means that the decision on the capital investment precedes the determination of the energy demand. It also implies that the substitution of energy for capital is more important than the substitution of capital for energy from the perspective of producer. This decision-making of a producer was also described in OTA (1993) which analyzed energy use in US industry. OTA (1993) reported that a producer's concern about energy efficiency, though prominent in a few energy-intensive industries, is minimal in most cases.

This explanation for asymmetry is reinforced by the data used in this study. Figure III-8 demonstrates the cost shares for capital and energy within the manufacturing sectors of the 10 OECD countries. The cost share for capital is the share of the sum of EK and NK costs to the total cost. Similarly, the cost share for energy is the share of the sum of electricity and fuel costs to the total cost. Figure 6 shows that in most countries, the cost share for capital is greater than the cost share for energy. Only in Korea, the opposite tendency is observed and thus, energy inputs and capital inputs substitute each other. Energy is a fairly small proportion of production costs in the manufacturing sector of most countries, and so naturally has played only a modest role in corporate decision-making (OTA, 1993). That is, a more sensitive response to price changes in capital inputs than in energy inputs seems to be reasonable from the perspective of the cost-minimizing producer (Kim, 2010). Thus, asymmetric substitutability between energy and capital is resulted from the behavior of the cost-minimizing producer.

Figure III-8. Cost Shares for Capital and Energy



These results are also explained by the employment of a static model. A static model assumes instantaneous adjustment in the capital stock to changes in fuel demand and the coincidence between a long-term equilibrium and a short-term equilibrium. That is, if fuel demand increases, the requisite capital stock needed to burn it magically increases. However, the capital stock and its characteristics are fixed in the short-run and they are variable in the long-run (Morrison, 1988). Thus, it is not enough to explain a long-term response of capital inputs to the price changes in energy inputs.

The asymmetric substitutability between energy and capital is useful for establishing an industrial energy policy. Firstly, it is likely that the capital investment to reduce energy consumption is not

expected when the energy price increases. In specific, the energy price policy (e.g. tax on energy) which aims to reduce energy demand by increasing its price will not produce actual effect. It is also supported by the highest own-price elasticities for fuel in general. Thus, a policy which stimulates investment in energy-efficient machinery in case of replacing equipment will be more effective. It also corresponds to the various studies on the effect of capital investment at the industry level (Kim, 2010; Velthuijsen, 1993).

6. Discussions and Implications

The Part III analyzes the substitutability between energy and capital after 1980, using data from the manufacturing sectors of 10 OECD countries. To find the generality and asymmetry of substitutability between energy and capital, the source of disagreement on the substitutability between energy and capital (*i.e.*, the assumption of input factors) and the direction of substitutability between them are contemplated. Five input factors, EK, NK, electricity, fuel, and *Other*, are assumed. In addition, the MES is utilized to measure asymmetric interfactor substitution.

To investigate the generality of substitutability between energy and capital, energy and capital are divided into sub-inputs: electricity, fuel, EK, and NK. The empirical results indicate that both electricity and fuel substitute for NK as well as EK in most of the countries analyzed. Substitutability of electricity by EK and NK is ambiguous and differs by country. However, in most cases, both EK and NK tend to complement fuel. That is, in general, energy inputs substitute for capital inputs, while capital inputs do not always. In particular, the separation of electricity and fuel is confirmed to be a major source of systematic variation in substitutability between energy and capital. This provides useful evidence for resolving arguments on the

“energy-capital hypothesis.”

In addition, the estimation results of MES show asymmetric substitution between energy and capital: substitution of energy for capital is dominant over substitution of capital for energy. This corresponds to the energy demand behavior (Hartman, 1979) that the decision on capital investment precedes the determination of energy demand in the industry. The cost for capital also is greater than the cost for energy in most countries. Thus, the dominant substitution of capital for energy is understandable from the perspective of the cost-minimizing producer. These results confirm that substitutability between energy and capital does not always mean the uptake of energy-saving technologies through capital investment. Furthermore, these results suggest that energy pricing is not sufficient to induce the adoption of energy-efficient technologies. It is meaningful because this study provides international evidences on the discussions of previous literatures (de Groot et al., 2001; Kim, 2010; OTA, 1993; Velthuijsen, 1993) on energy-saving policy options by the empirical analysis of the KLEM model.

The major results of this study can be reinforced by the following further study. I used a static model, where capital is treated analogously to the other inputs. However, the capital stock and its characteristics are fixed in the short-run and they are variable in the

long-run (Morrison, 1988). Hereafter, if a dynamic model that allows us to separate long-term and short-term effects is employed, more useful implications for industrial energy policy could be derived. In addition, this study does not clearly show the difference in substitutability by capital type. The reason is that it is hard to classify capital assets based on the actual energy use due to data availability. If capital assets are divided by their energy consumption characteristics, the source of disagree on substitutability between energy and capital will be made clear.

CONCLUSIONS

1. Summary of the Results

This thesis contemplates separability and substitutability between energy and capital in the framework of the KLEM model (Berndt and Wood, 1975), which has been an important issue for energy economists because it measures the uptake of energy-saving technologies through capital investment. Starting with the theoretical issue of *separability* between energy and capital, this thesis suggests a new way to analyze substitutability between energy and capital. It also analyzes whether energy-saving technologies have been adopted and finds some policy implications for industrial energy demand. To develop a general discussion, the manufacturing sectors of the following 10 OECD countries are separately analyzed: Australia Austria, Denmark, Finland, Italy, Japan, Korea, the Netherlands, the UK, and the US. Some possible answers to the three research questions are as follows.

First, is it appropriate to assume that energy is separable from capital? Part I deals with this research question in earnest. The concept of separability is designed to allow the convenience of applied study as well as ease of interpretation. Applying Denny and

Fuss (1977)'s method, three cases and sixteen separability patterns are tested. The test results for *Case 1* reveal that the capital aggregate and the energy aggregate are not weakly separable from each other. The test results for *Case 2* tell us that the three capital assets cannot be aggregated consistently. Finally, the results for *Case 3* show that it is hard to aggregate four energy sources in most of the countries under study. The empirical results of Part I thus imply that separability between energy and capital, which has been conventionally assumed to be possible in many applied studies of the KLEM model, is not in general theoretically permissible. Thus, Part I shows the need to divide energy and capital into sub-inputs at a manageable level in the application of the KLEM model.

Second, are demand for coal, oil, gas, and electricity differentiated by investment of individual capital assets? To answer this question, the energy sub-model (Fuss, 1977)—in other words, a sub-part of the KLEM model—is extended by adding a variable reflecting capital investment. To measure the effect of several capital assets, components of the capital aggregate are defined by reference to the previous literature (BEA, 2003; Christensen and Jorgenson, 1969; Field and Grebenstein, 1980; Garofalo and Malhotra, 1988; OECD, 2001; Pyo, 2003; SNA, 1993; Timmer et al., 2007). There are six types of capital assets that are components of the capital aggregate:

ICT assets; transport equipment; other machinery; other assets; non-residential structures; and residential structures.

The empirical results show that ICT assets increase electricity demand and decrease both coal and oil demand. Transport equipment affects demand for these four energy sources in an opposite way to ICT assets. Based on effect on electricity demand, the six types of capital asset can be classified into capital that increases the electricity demand (EK) and capital that does not (NK). ICT assets, other machinery, and other assets can be classified as EK, and transport equipment, non-residential structures, and residential structures as NK.

Given these results, an extended energy sub-model for investment of EK and NK is proposed. Comparing the estimation results of the energy sub-model with the extended energy sub-model, we find that the latter reveals generally better performance than the former. Interfuel substitutability derived by both models is compared, as well. Compared to the energy sub-model, in the extended model both the direction and the magnitude of interfuel substitutability change in most of countries. However, no special tendency is observed in these changes. In addition, the international comparison also shows that the higher energy independence, the lower interfuel substitutability.

The estimation results of the extended energy sub-model for EK

and NK imply that the incorporation of capital investment into the energy sub-model is appropriate. This implication is also supported by the results of Part I, which show that energy and capital are not weakly separable from each other.

Third, can energy be substituted by capital? Part III conducts an intensive analysis of this issue, and thus of "the energy–capital hypothesis" raised by Griffin and Gregory (1976). Applying the KLEM model (Berndt and Wood, 1975), the features of substitutability between energy and capital are investigated. In particular, the source of disagreement on substitutability between energy and capital (*i.e.*, the assumption of input factors) and the direction of substitutability between them are contemplated. Five input factors—EK, NK, electricity, fuel, and *Other* (the aggregate of labor and material)—are assumed. To find the direction of substitution, the concept of Morishima elasticity of substitution (MES) (Blackorby and Russell, 1989; Morishima, 1967), which measures asymmetric substitutability, is utilized.

The empirical results tell us that both NK and EK substitute electricity as well as fuel in most of the countries under study. The overall situation regarding substitution of EK and NK for electricity is ambiguous, as it varies by country. However, in most cases, both EK and NK tend to complement fuel. That is, energy inputs can be

substituted by capital inputs, but capital inputs do not always. In particular, the difference between substitutability between of electricity by capital and substitutability of fuel by capital is confirmed as a major divergence and thus a major source of disagreement on this issue. In addition, no specific tendency of interfactor substitutability by country type is observed.

Finally, the MES estimation results show that substitution of energy for capital dominates substitution of capital for energy. This asymmetry corresponds to “the energy demand behavior” (Hartman, 1979) wherein the decision on capital investment precedes the determination of energy demand in an industry. The cost of capital is also greater than the cost of energy. Thus, it is not likely that capital substitutes for energy in the event of an increase in energy price. Moreover, capital stock has difficulty responding flexibly to energy price changes, because it is fixed in the short run and variable in the long run (Morrison, 1988). Putting these results together, we see that substitutability between energy and capital does not necessarily mean the uptake of energy-saving technologies through capital investment.

In sum, this thesis conducts an in-depth investigation of separability and substitutability between energy and capital. Part I shows that in the empirical study of the KLEM model, it is better to divide energy and capital into sub-inputs. Then, Part II shows us how

to divide these inputs with consideration to data availability and input interaction. Finally, Part III finds a source of systematic variation in substitutability between energy and capital and provides generalized results relating to this issue.

2. Contributions

The contributions of this thesis are summarized in five points. The first contribution refers to a theoretical contribution on the KLEM model. This thesis is the first study which examines in earnest separability between energy and capital in both theoretical and empirical ways. The result that energy and capital are not weakly separable can be a useful reference for applied studies of the KLEM model.

The second point is the contribution on the classification of capital assets. This thesis shows that the demands of energy sources are affected by the investment of various capital assets. Unlike previous studies on classifying capital assets, this thesis classify several capital assets into two types based on their effects on the electricity demand. This classification is expected to give a new insight to the related arguments.

The generalization of substitutability between energy and capital in the ten major countries is the third contribution. Starting from the issue of separability, substitutability between energy and capital is precisely investigated. This thesis confirms that the separation of electricity and fuel is a major source of disagree on “the energy-capital hypothesis.” It also founds that substitution of energy for

capital is dominant over substitution of capital for energy in the all countries analyzed.

The fourth point refers to the implication for industrial energy policy. The asymmetric substitutability between energy and capital indicates that substitutability does not always mean an adoption of energy-saving technologies through capital investment. Consequently, this result implies that energy-pricing seems to be ineffective because capital does not substitute capital well. This thesis provides international evidences on the discussions of previous studies on energy-saving policy options (de Groot et al., 2001; Kim, 2010; OTA, 1993; Velthuijsen, 1993).

The last contribution of this thesis is the theoretical contribution to the theory of economic growth. This thesis compares interfactor substitutability as well as interfuel substitutability of the manufacturing sectors in the ten OECD countries. The result shows that the higher energy independence, the lower interfuel substitutability. However, a certain tendency of interfactor substitutability by country type does not observed. This reflects the differences of the production structure of each country.

APPPENDIX I

1. Case 1: Parameter Estimates of Eq. (I-13)

Table A-I-1. Parameter Estimates of Case 1 (Australia)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{K_I}	0.0956	(0.000)	$\beta_{K_M E_G}$	-0.0443	(0.000)
β_{K_M}	0.5294	(0.000)	$\beta_{K_M E_E}$	-0.1093	(0.000)
β_{K_B}	0.3123	(0.000)	$\beta_{K_B K_B}$	0.1316	(0.000)
β_{E_C}	0.0208	(0.000)	$\beta_{K_B E_C}$	-0.0088	(0.000)
β_{E_O}	-0.0176	0.537)	$\beta_{K_B E_O}$	-0.0712	(0.000)
β_{E_G}	0.0929	(0.000)	$\beta_{K_B E_G}$	-0.0023	(0.573)
β_{E_E}	-0.0333	(0.061)	$\beta_{K_B E_E}$	0.0197	(0.019)
$\beta_{K_I K_I}$	-0.0113	(0.000)	$\beta_{E_C E_C}$	0.0143	(0.000)
$\beta_{K_I K_M}$	0.0056	(0.033)	$\beta_{E_C E_O}$	0.0031	(0.388)
$\beta_{K_I K_B}$	0.0108	(0.000)	$\beta_{E_C E_G}$	-0.0031	(0.041)
$\beta_{K_I E_C}$	0.0048	(0.000)	$\beta_{E_C E_E}$	-0.0030	(0.346)
$\beta_{K_I E_O}$	0.0116	(0.011)	$\beta_{E_O E_O}$	0.0876	(0.036)
$\beta_{K_I E_G}$	0.0012	(0.354)	$\beta_{E_O E_G}$	-0.0185	(0.132)
$\beta_{K_I E_E}$	-0.0227	(0.000)	$\beta_{E_O E_E}$	-0.0460	(0.035)
$\beta_{K_M K_M}$	0.2015	(0.000)	$\beta_{E_G E_G}$	0.0941	(0.000)
$\beta_{K_M K_B}$	-0.0797	(0.000)	$\beta_{E_G E_E}$	-0.0270	(0.000)
$\beta_{K_M E_C}$	-0.0072	(0.000)	$\beta_{E_E E_E}$	0.1883	(0.000)
$\beta_{K_M E_O}$	0.0335	(0.139)			
Log likelihood		672.8037	Observation		28

[a] K_I: ICT assets, K_M: Machinery, K_B: Buildings; E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-I-2. Parameter Estimates of Case 1 (Austria)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{K_I}	0.0642	(0.000)	$\beta_{K_M E_G}$	-0.0446	(0.000)
β_{K_M}	0.4928	(0.000)	$\beta_{K_M E_E}$	-0.0428	(0.000)
β_{K_B}	0.4535	(0.000)	$\beta_{K_B K_B}$	0.1655	(0.000)
β_{E_C}	0.0174	(0.046)	$\beta_{K_B E_C}$	0.0129	(0.001)
β_{E_O}	-0.0621	(0.000)	$\beta_{K_B E_O}$	-0.0244	(0.000)
β_{E_G}	-0.0159	(0.023)	$\beta_{K_B E_G}$	-0.0244	(0.000)
β_{E_E}	0.0502	(0.001)	$\beta_{K_B E_E}$	-0.0614	(0.000)
$\beta_{K_I K_I}$	-0.0013	(0.691)	$\beta_{E_C E_C}$	0.0175	(0.010)
$\beta_{K_I K_M}$	0.0159	(0.000)	$\beta_{E_C E_O}$	-0.0075	(0.069)
$\beta_{K_I K_B}$	0.0117	(0.000)	$\beta_{E_C E_G}$	0.0160	(0.000)
$\beta_{K_I E_C}$	-0.0039	(0.086)	$\beta_{E_C E_E}$	0.0016	(0.700)
$\beta_{K_I E_O}$	-0.0008	(0.742)	$\beta_{E_O E_O}$	-0.0134	(0.014)
$\beta_{K_I E_G}$	-0.0165	(0.000)	$\beta_{E_O E_G}$	0.0112	(0.000)
$\beta_{K_I E_E}$	-0.0051	(0.127)	$\beta_{E_O E_E}$	0.0367	(0.000)
$\beta_{K_M K_M}$	0.2162	(0.000)	$\beta_{E_G E_G}$	-0.0080	(0.103)
$\beta_{K_M K_B}$	-0.1061	(0.000)	$\beta_{E_G E_E}$	0.0400	(0.000)
$\beta_{K_M E_C}$	-0.0365	(0.000)	$\beta_{E_E E_E}$	0.0311	(0.002)
$\beta_{K_M E_O}$	-0.0019	(0.734)			
Log likelihood		722.0617	Observation		28

[a] K_I: ICT assets, K_M: Machinery, K_B: Buildings; E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-I-3. Parameter Estimates of Case 1(Denmark)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{K_I}	0.0160	(0.072)	$\beta_{K_M E_G}$	-0.0098	(0.079)
β_{K_M}	0.7799	(0.000)	$\beta_{K_M E_E}$	-0.0552	(0.000)
β_{K_B}	0.4770	(0.000)	$\beta_{K_B K_B}$	0.1390	(0.000)
β_{E_C}	0.0001	(0.988)	$\beta_{K_B E_C}$	-0.0081	(0.000)
β_{E_O}	0.0427	(0.001)	$\beta_{K_B E_O}$	-0.0025	(0.279)
β_{E_G}	-0.0611	(0.001)	$\beta_{K_B E_G}$	-0.0046	(0.246)
β_{E_E}	-0.2545	(0.000)	$\beta_{K_B E_E}$	-0.0349	(0.000)
$\beta_{K_I K_I}$	-0.0237	(0.000)	$\beta_{E_C E_C}$	0.0137	(0.000)
$\beta_{K_I K_M}$	-0.0032	(0.157)	$\beta_{E_C E_O}$	-0.0013	(0.402)
$\beta_{K_I K_B}$	-0.0059	(0.006)	$\beta_{E_C E_G}$	-0.0008	(0.744)
$\beta_{K_I E_C}$	0.0026	(0.000)	$\beta_{E_C E_E}$	-0.0055	(0.006)
$\beta_{K_I E_O}$	0.0258	(0.000)	$\beta_{E_O E_O}$	0.1450	(0.000)
$\beta_{K_I E_G}$	-0.0029	(0.394)	$\beta_{E_O E_G}$	-0.0895	(0.000)
$\beta_{K_I E_E}$	0.0073	(0.000)	$\beta_{E_O E_E}$	-0.0244	(0.000)
$\beta_{K_M K_M}$	0.2049	(0.000)	$\beta_{E_G E_G}$	0.1128	(0.000)
$\beta_{K_M K_B}$	-0.0829	(0.000)	$\beta_{E_G E_E}$	-0.0052	(0.210)
$\beta_{K_M E_C}$	-0.0006	(0.742)	$\beta_{E_E E_E}$	0.1180	(0.000)
$\beta_{K_M E_O}$	-0.0531	(0.000)			
Log likelihood		582.9058	Observation		24

[a] K_I: ICT assets, K_M: Machinery, K_B: Buildings; E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-I-4. Parameter Estimates of Case 1 (Finland)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{K_I}	0.0971	(0.000)	$\beta_{K_M E_G}$	-0.0145	(0.000)
β_{K_M}	0.5624	(0.000)	$\beta_{K_M E_E}$	-0.0689	(0.000)
β_{K_B}	0.3664	(0.000)	$\beta_{K_B K_B}$	0.1440	(0.000)
β_{E_C}	0.0606	(0.000)	$\beta_{K_B E_C}$	-0.0097	(0.000)
β_{E_O}	-0.0502	(0.056)	$\beta_{K_B E_O}$	-0.0421	(0.000)
β_{E_G}	0.0295	(0.000)	$\beta_{K_B E_G}$	-0.0052	(0.000)
β_{E_E}	-0.0628	(0.005)	$\beta_{K_B E_E}$	-0.0166	(0.048)
$\beta_{K_I K_I}$	-0.0393	(0.000)	$\beta_{E_C E_C}$	0.0506	(0.000)
$\beta_{K_I K_M}$	0.0127	(0.000)	$\beta_{E_C E_O}$	-0.0213	(0.001)
$\beta_{K_I K_B}$	0.0190	(0.000)	$\beta_{E_C E_G}$	0.0013	(0.519)
$\beta_{K_I E_C}$	0.0029	(0.432)	$\beta_{E_C E_E}$	-0.0070	(0.421)
$\beta_{K_I E_O}$	0.0097	(0.134)	$\beta_{E_O E_O}$	0.1120	(0.002)
$\beta_{K_I E_G}$	0.0004	(0.734)	$\beta_{E_O E_G}$	0.0043	(0.09)
$\beta_{K_I E_E}$	-0.0056	(0.426)	$\beta_{E_O E_E}$	0.0037	(0.850)
$\beta_{K_M K_M}$	0.2433	(0.000)	$\beta_{E_G E_G}$	0.0206	(0.000)
$\beta_{K_M K_B}$	-0.0894	(0.000)	$\beta_{E_G E_E}$	-0.0070	(0.001)
$\beta_{K_M E_C}$	-0.0168	(0.000)	$\beta_{E_E E_E}$	0.1014	(0.000)
$\beta_{K_M E_O}$	-0.0664	(0.001)			
Log likelihood		604.6550	Observation		28

[a] K_I: ICT assets, K_M: Machinery, K_B: Buildings; E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-I-5. Parameter Estimates of Case 1 (Italy)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{K_I}	0.1288	(0.000)	$\beta_{K_M E_G}$	-0.0003	(0.915)
β_{K_M}	0.7248	(0.000)	$\beta_{K_M E_E}$	-0.0802	(0.000)
β_{K_B}	0.3758	(0.000)	$\beta_{K_B K_B}$	0.1402	(0.000)
β_{E_C}	-0.0032	(0.306)	$\beta_{K_B E_C}$	-0.0000	(0.996)
β_{E_O}	-0.1329	(0.000)	$\beta_{K_B E_O}$	-0.0215	(0.000)
β_{E_G}	0.0535	(0.000)	$\beta_{K_B E_G}$	-0.0059	(0.002)
β_{E_E}	-0.1469	(0.000)	$\beta_{K_B E_E}$	-0.0227	(0.000)
$\beta_{K_I K_I}$	-0.0042	(0.015)	$\beta_{E_C E_C}$	0.0011	(0.228)
$\beta_{K_I K_M}$	0.0408	(0.000)	$\beta_{E_C E_O}$	0.0017	(0.208)
$\beta_{K_I K_B}$	-0.0034	(0.016)	$\beta_{E_C E_G}$	0.0043	(0.083)
$\beta_{K_I E_C}$	-0.0012	(0.096)	$\beta_{E_C E_E}$	0.0036	(0.011)
$\beta_{K_I E_O}$	-0.0213	(0.000)	$\beta_{E_O E_O}$	0.2156	(0.000)
$\beta_{K_I E_G}$	0.0145	(0.000)	$\beta_{E_O E_G}$	-0.0030	(0.476)
$\beta_{K_I E_E}$	-0.0252	(0.000)	$\beta_{E_O E_E}$	-0.0295	(0.000)
$\beta_{K_M K_M}$	0.2779	(0.000)	$\beta_{E_G E_G}$	0.0071	(0.420)
$\beta_{K_M K_B}$	-0.0867	(0.000)	$\beta_{E_G E_E}$	-0.0168	(0.000)
$\beta_{K_M E_C}$	-0.0095	(0.000)	$\beta_{E_E E_E}$	0.1709	(0.000)
$\beta_{K_M E_O}$	-0.1419	(0.000)			
Log likelihood		759.5705	Observation		28

[a] K_I: ICT assets, K_M: Machinery, K_B: Buildings; E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-I-6. Parameter Estimates of Case 1 (Japan)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{K_I}	-0.2890	(0.000)	$\beta_{K_M E_G}$	-0.0008	(0.566)
β_{K_M}	0.3598	(0.000)	$\beta_{K_M E_E}$	-0.0060	(0.437)
β_{K_B}	1.0274	(0.000)	$\beta_{K_B K_B}$	0.1698	(0.000)
β_{E_C}	0.0126	(0.079)	$\beta_{K_B E_C}$	-0.0075	(0.000)
β_{E_O}	0.0921	(0.000)	$\beta_{K_B E_O}$	-0.0325	(0.000)
β_{E_G}	-0.0206	(0.000)	$\beta_{K_B E_G}$	-0.0035	(0.010)
β_{E_E}	-0.1824	(0.003)	$\beta_{K_B E_E}$	-0.0601	(0.000)
$\beta_{K_I K_I}$	0.0061	(0.148)	$\beta_{E_C E_C}$	0.0100	(0.000)
$\beta_{K_I K_M}$	-0.0931	(0.000)	$\beta_{E_C E_O}$	0.0017	(0.000)
$\beta_{K_I K_B}$	0.0306	(0.000)	$\beta_{E_C E_G}$	0.0010	(0.092)
$\beta_{K_I E_C}$	0.0041	(0.000)	$\beta_{E_C E_E}$	-0.0094	(0.000)
$\beta_{K_I E_O}$	0.0191	(0.000)	$\beta_{E_O E_O}$	0.0243	(0.000)
$\beta_{K_I E_G}$	-0.0010	(0.376)	$\beta_{E_O E_G}$	0.0004	(0.164)
$\beta_{K_I E_E}$	0.0343	(0.000)	$\beta_{E_O E_E}$	-0.0317	(0.000)
$\beta_{K_M K_M}$	0.1780	(0.000)	$\beta_{E_G E_G}$	0.0062	(0.000)
$\beta_{K_M K_B}$	-0.0969	(0.000)	$\beta_{E_G E_E}$	-0.0024	(0.269)
$\beta_{K_M E_C}$	0.0002	(0.855)	$\beta_{E_E E_E}$	0.0752	(0.000)
$\beta_{K_M E_O}$	0.0187	(0.000)			
Log likelihood		776.6272	Observation		27

[a] K_I: ICT assets, K_M: Machinery, K_B: Buildings; E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-I-7. Parameter Estimates of Case 1 (Korea)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{K_I}	0.1382	(0.000)	$\beta_{K_M E_G}$	0.0099	(0.011)
β_{K_M}	1.7463	(0.000)	$\beta_{K_M E_E}$	-0.1001	(0.000)
β_{K_B}	0.6104	(0.000)	$\beta_{K_B K_B}$	0.0937	(0.000)
β_{E_C}	-0.0086	(0.155)	$\beta_{K_B E_C}$	-0.0017	(0.000)
β_{E_O}	-0.2340	(0.000)	$\beta_{K_B E_O}$	-0.0080	(0.005)
β_{E_G}	-0.0027	(0.911)	$\beta_{K_B E_G}$	-0.0031	(0.052)
β_{E_E}	-1.2495	(0.000)	$\beta_{K_B E_E}$	-0.0351	(0.000)
$\beta_{K_I K_I}$	0.0366	(0.000)	$\beta_{E_C E_C}$	-0.0035	(0.001)
$\beta_{K_I K_M}$	-0.0213	(0.004)	$\beta_{E_C E_O}$	0.0003	(0.755)
$\beta_{K_I K_B}$	-0.0059	(0.000)	$\beta_{E_C E_G}$	0.0011	(0.221)
$\beta_{K_I E_C}$	0.0114	(0.000)	$\beta_{E_C E_E}$	0.0024	(0.002)
$\beta_{K_I E_O}$	0.0244	(0.000)	$\beta_{E_O E_O}$	-0.0334	(0.000)
$\beta_{K_I E_G}$	-0.0145	(0.000)	$\beta_{E_O E_G}$	0.0104	(0.107)
$\beta_{K_I E_E}$	-0.0307	(0.000)	$\beta_{E_O E_E}$	0.0623	(0.000)
$\beta_{K_M K_M}$	0.2174	(0.000)	$\beta_{E_G E_G}$	0.0275	(0.000)
$\beta_{K_M K_B}$	-0.0399	(0.000)	$\beta_{E_G E_E}$	-0.0312	(0.000)
$\beta_{K_M E_C}$	-0.0101	(0.000)	$\beta_{E_E E_E}$	0.1323	(0.000)
$\beta_{K_M E_O}$	-0.0560	(0.000)			
Log likelihood		594.3282	Observation		23

[a] K_I: ICT assets, K_M: Machinery, K_B: Buildings; E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-I-8. Parameter Estimates of Case 1 (Netherlands)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{K_I}	0.1299	(0.000)	$\beta_{K_M E_G}$	-0.1006	(0.000)
β_{K_M}	0.5463	(0.000)	$\beta_{K_M E_E}$	-0.0289	(0.000)
β_{K_B}	0.3771	(0.000)	$\beta_{K_B K_B}$	0.1283	(0.000)
β_{E_C}	0.0301	(0.000)	$\beta_{K_B E_C}$	0.0057	(0.000)
β_{E_O}	-0.0526	(0.072)	$\beta_{K_B E_O}$	0.0085	(0.332)
β_{E_G}	0.0573	(0.004)	$\beta_{K_B E_G}$	-0.0215	(0.000)
β_{E_E}	-0.0880	(0.000)	$\beta_{K_B E_E}$	-0.0563	(0.000)
$\beta_{K_I K_I}$	0.0032	(0.754)	$\beta_{E_C E_C}$	0.0138	(0.000)
$\beta_{K_I K_M}$	0.0222	(0.164)	$\beta_{E_C E_O}$	-0.0061	(0.014)
$\beta_{K_I K_B}$	0.0073	(0.181)	$\beta_{E_C E_G}$	-0.0108	(0.000)
$\beta_{K_I E_C}$	0.0082	(0.000)	$\beta_{E_C E_E}$	-0.0033	(0.123)
$\beta_{K_I E_O}$	-0.0283	(0.079)	$\beta_{E_O E_O}$	0.0717	(0.020)
$\beta_{K_I E_G}$	0.0061	(0.508)	$\beta_{E_O E_G}$	0.0449	(0.000)
$\beta_{K_I E_E}$	-0.0187	(0.000)	$\beta_{E_O E_E}$	-0.0024	(0.771)
$\beta_{K_M K_M}$	0.2751	(0.000)	$\beta_{E_G E_G}$	0.0573	(0.004)
$\beta_{K_M K_B}$	-0.0720	(0.000)	$\beta_{E_G E_E}$	-0.0483	(0.000)
$\beta_{K_M E_C}$	-0.0075	(0.009)	$\beta_{E_E E_E}$	0.1580	(0.000)
$\beta_{K_M E_O}$	-0.0883	(0.002)			
Log likelihood		676.4336	Observation		28

[a] K_I: ICT assets, K_M: Machinery, K_B: Buildings; E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-I-9. Parameter Estimates of Case 1 (UK)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{K_I}	0.1445	(0.000)	$\beta_{K_M E_G}$	-0.0650	(0.000)
β_{K_M}	0.4621	(0.000)	$\beta_{K_M E_E}$	-0.0306	(0.000)
β_{K_B}	0.2676	(0.000)	$\beta_{K_B K_B}$	0.1070	(0.000)
β_{E_C}	0.0008	(0.933)	$\beta_{K_B E_C}$	0.0048	(0.315)
β_{E_O}	0.0581	(0.000)	$\beta_{K_B E_O}$	-0.0187	(0.001)
β_{E_G}	0.0550	(0.000)	$\beta_{K_B E_G}$	-0.0057	(0.019)
β_{E_E}	0.0119	(0.413)	$\beta_{K_B E_E}$	-0.0335	(0.000)
$\beta_{K_I K_I}$	-0.0092	(0.100)	$\beta_{E_C E_C}$	0.0505	(0.000)
$\beta_{K_I K_M}$	0.0425	(0.000)	$\beta_{E_C E_O}$	-0.0119	(0.107)
$\beta_{K_I K_B}$	0.0012	(0.624)	$\beta_{E_C E_G}$	-0.0207	(0.000)
$\beta_{K_I E_C}$	-0.0276	(0.000)	$\beta_{E_C E_E}$	0.0321	(0.000)
$\beta_{K_I E_O}$	0.0207	(0.000)	$\beta_{E_O E_O}$	0.0561	(0.000)
$\beta_{K_I E_G}$	0.0163	(0.001)	$\beta_{E_O E_G}$	0.0356	(0.000)
$\beta_{K_I E_E}$	-0.0439	(0.000)	$\beta_{E_O E_E}$	-0.0477	(0.000)
$\beta_{K_M K_M}$	0.1694	(0.000)	$\beta_{E_G E_G}$	0.0659	(0.000)
$\beta_{K_M K_B}$	-0.0550	(0.000)	$\beta_{E_G E_E}$	-0.0264	(0.000)
$\beta_{K_M E_C}$	-0.0272	(0.000)	$\beta_{E_E E_E}$	0.1500	(0.000)
$\beta_{K_M E_O}$	-0.0341	(0.000)			
Log likelihood		615.7425	Observation		28

[a] K_I: ICT assets, K_M: Machinery, K_B: Buildings; E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-I-10. Parameter Estimates of Case 1 (US)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{K_I}	0.0809	(0.000)	$\beta_{K_M E_G}$	-0.0343	(0.000)
β_{K_M}	0.4378	(0.000)	$\beta_{K_M E_E}$	-0.0330	(0.000)
β_{K_B}	0.3479	(0.000)	$\beta_{K_B K_B}$	0.1561	(0.000)
β_{E_C}	0.0625	(0.000)	$\beta_{K_B E_C}$	0.0061	(0.024)
β_{E_O}	0.0074	(0.324)	$\beta_{K_B E_O}$	-0.0375	(0.000)
β_{E_G}	0.1063	(0.000)	$\beta_{K_B E_G}$	-0.0383	(0.000)
β_{E_E}	-0.0428	(0.006)	$\beta_{K_B E_E}$	-0.0324	(0.000)
$\beta_{K_I K_I}$	-0.0595	(0.000)	$\beta_{E_C E_C}$	0.0316	(0.000)
$\beta_{K_I K_M}$	-0.0025	(0.407)	$\beta_{E_C E_O}$	-0.0030	(0.005)
$\beta_{K_I K_B}$	0.0216	(0.000)	$\beta_{E_C E_G}$	0.0024	(0.009)
$\beta_{K_I E_C}$	0.0003	(0.850)	$\beta_{E_C E_E}$	-0.0207	(0.000)
$\beta_{K_I E_O}$	-0.0083	(0.070)	$\beta_{E_O E_O}$	0.1386	(0.000)
$\beta_{K_I E_G}$	0.0251	(0.000)	$\beta_{E_O E_G}$	0.0011	(0.813)
$\beta_{K_I E_E}$	0.0232	(0.000)	$\beta_{E_O E_E}$	-0.0420	(0.000)
$\beta_{K_M K_M}$	0.2112	(0.000)	$\beta_{E_G E_G}$	0.0980	(0.000)
$\beta_{K_M K_B}$	-0.0757	(0.000)	$\beta_{E_G E_E}$	-0.0541	(0.000)
$\beta_{K_M E_C}$	-0.0168	(0.001)	$\beta_{E_E E_E}$	0.1590	(0.000)
$\beta_{K_M E_O}$	-0.0490	(0.000)			
Log likelihood		671.3127	Observation		28

[a] K_I: ICT assets, K_M: Machinery, K_B: Buildings; E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

2. Case 2: Parameter Estimates of Eq. (I-15)

Table A-I-11. Parameter Estimates of Case 2 (Australia)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{K_I}	0.0807	(0.000)	β_{K_IE}	-0.0050	(0.056)
β_{K_M}	0.6630	(0.000)	$\beta_{K_MK_M}$	0.1929	(0.000)
β_{K_B}	0.389	(0.000)	$\beta_{K_MK_B}$	-0.0717	(0.000)
β_E	-0.1329	(0.000)	β_{K_ME}	-0.1300	(0.000)
$\beta_{K_IK_I}$	-0.0115	(0.000)	$\beta_{K_BK_B}$	0.1291	(0.000)
$\beta_{K_IK_M}$	0.0088	(0.000)	β_{K_BE}	-0.0650	(0.000)
$\beta_{K_IK_B}$	0.0077	(0.001)	β_{EE}	0.2000	(0.000)
Log likelihood		273.9965	Observation		28

[a] K_I: ICT assets, K_M: Machinery, K_B: Buildings; E: Energy aggregate

Table A-I-12. Parameter Estimates of Case 2 (Austria)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{K_I}	0.0822	(0.000)	β_{K_IE}	-0.0170	(0.075)
β_{K_M}	0.5828	(0.000)	$\beta_{K_MK_M}$	0.1873	(0.000)
β_{K_B}	0.4658	(0.000)	$\beta_{K_MK_B}$	-0.0958	(0.000)
β_E	-0.1308	(0.000)	β_{K_ME}	-0.0978	(0.000)
$\beta_{K_IK_I}$	-0.0049	(0.274)	$\beta_{K_BK_B}$	0.1607	(0.000)
$\beta_{K_IK_M}$	0.0063	(0.345)	β_{K_BE}	-0.0805	(0.000)
$\beta_{K_IK_B}$	0.0156	(0.000)	β_{EE}	0.1954	(0.000)
Log likelihood		305.9319	Observation		28

[a] K_I: ICT assets, K_M: Machinery, K_B: Buildings; E: Energy aggregate

Table A-I-13. Parameter Estimates of Case 2 (Denmark)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{K_I}	0.0879	(0.000)	β_{K_IE}	0.0224	(0.000)
β_{K_M}	0.5105	(0.000)	$\beta_{K_MK_M}$	0.1906	(0.000)
β_{K_B}	0.3840	(0.000)	$\beta_{K_MK_B}$	-0.0806	(0.000)
β_E	0.0176	(0.111)	β_{K_ME}	-0.1066	(0.000)
$\beta_{K_IK_I}$	-0.0205	(0.000)	$\beta_{K_BK_B}$	0.1474	(0.000)
$\beta_{K_IK_M}$	-0.0034	(0.046)	β_{K_BE}	-0.0684	(0.000)
$\beta_{K_IK_B}$	0.0015	(0.656)	β_{EE}	0.1525	(0.000)
Log likelihood		265.8063	Observation		24

[a] K_I: ICT assets, K_M: Machinery, K_B: Buildings; E: Energy aggregate

Table A-I-14. Parameter Estimates of Case 2 (Finland)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{K_I}	0.1057	(0.000)	β_{K_IE}	-0.0103	(0.138)
β_{K_M}	0.5628	(0.000)	$\beta_{K_MK_M}$	0.2397	(0.000)
β_{K_B}	0.3683	(0.000)	$\beta_{K_MK_B}$	-0.0929	(0.000)
β_E	-0.0368	(0.005)	β_{K_ME}	-0.1615	(0.000)
$\beta_{K_IK_I}$	-0.0288	(0.000)	$\beta_{K_BK_B}$	0.1349	(0.000)
$\beta_{K_IK_M}$	0.0147	(0.002)	β_{K_BE}	-0.0664	(0.000)
$\beta_{K_IK_B}$	0.0244	(0.000)	β_{EE}	0.2383	(0.000)
Log likelihood		267.9904	Observation		28

[a] K_I: ICT assets, K_M: Machinery, K_B: Buildings; E: Energy aggregate

Table A-I-15. Parameter Estimates of Case 2 (Italy)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{K_I}	0.1278	(0.000)	β_{K_IE}	-0.0418	(0.000)
β_{K_M}	0.8343	(0.000)	$\beta_{K_MK_M}$	0.2665	(0.000)
β_{K_B}	0.3922	(0.000)	$\beta_{K_MK_B}$	-0.0893	(0.000)
β_E	-0.3543	(0.000)	β_{K_ME}	-0.2251	(0.000)
$\beta_{K_IK_I}$	0.0006	(0.837)	$\beta_{K_BK_B}$	0.1399	(0.000)
$\beta_{K_IK_M}$	0.0478	(0.000)	β_{K_BE}	-0.0440	(0.000)
$\beta_{K_IK_B}$	-0.0067	(0.001)	β_{EE}	0.3108	(0.000)
Log likelihood		317.4378	Observation		28

[a] K_I: ICT assets, K_M: Machinery, K_B: Buildings; E: Energy aggregate

Table A-I-16. Parameter Estimates of Case 2 (Japan)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{K_I}	-0.0114	(0.506)	β_{K_IE}	0.0614	(0.000)
β_{K_M}	0.3953	(0.000)	$\beta_{K_MK_M}$	0.1747	(0.000)
β_{K_B}	0.5247	(0.000)	$\beta_{K_MK_B}$	-0.0921	(0.000)
β_E	0.0914	(0.000)	β_{K_ME}	0.0202	(0.031)
$\beta_{K_IK_I}$	0.0008	(0.881)	$\beta_{K_BK_B}$	0.1632	(0.000)
$\beta_{K_IK_M}$	-0.1028	(0.000)	β_{K_BE}	-0.1116	(0.000)
$\beta_{K_IK_B}$	0.0406	(0.000)	β_{EE}	0.0300	(0.005)
Log likelihood		297.2207	Observation		27

[a] K_I: ICT assets, K_M: Machinery, K_B: Buildings; E: Energy aggregate

Table A-I-17. Parameter Estimates of Case 2 (Korea)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{K_I}	-0.0026	(0.728)	β_{K_IE}	0.0039	(0.256)
β_{K_M}	0.6589	(0.000)	$\beta_{K_MK_M}$	0.2659	(0.000)
β_{K_B}	0.2688	(0.000)	$\beta_{K_MK_B}$	-0.0460	(0.000)
β_E	0.0749	(0.093)	β_{K_ME}	-0.1379	(0.000)
$\beta_{K_IK_I}$	0.0864	(0.000)	$\beta_{K_BK_B}$	0.0945	(0.000)
$\beta_{K_IK_M}$	-0.0820	(0.000)	β_{K_BE}	-0.0402	(0.000)
$\beta_{K_IK_B}$	-0.0083	(0.000)	β_{EE}	0.1742	(0.000)
Log likelihood		231.9714	Observation		23

[a] K_I: ICT capital, K_M: Machinery, K_B: Buildings; E: Energy aggregate

Table A-I-18. Parameter Estimates of Case 2 (Netherlands)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{K_I}	0.1548	(0.000)	β_{K_IE}	-0.0728	(0.000)
β_{K_M}	0.6556	(0.000)	$\beta_{K_MK_M}$	0.2944	(0.000)
β_{K_B}	0.3280	(0.000)	$\beta_{K_MK_B}$	-0.0769	(0.000)
β_E	-0.1384	(0.000)	β_{K_ME}	-0.2633	(0.000)
$\beta_{K_IK_I}$	0.0218	(0.000)	$\beta_{K_BK_B}$	0.1280	(0.000)
$\beta_{K_IK_M}$	0.0457	(0.000)	β_{K_BE}	-0.0564	(0.000)
$\beta_{K_IK_B}$	0.0053	(0.270)	β_{EE}	0.3925	(0.000)
Log likelihood		305.5954	Observation		28

[a] K_I: ICT assets, K_M: Machinery, K_B: Buildings; E: Energy aggregate

Table A-I-19. Parameter Estimates of Case 2 (UK)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{K_I}	0.1466	(0.000)	β_{K_IE}	-0.0169	(0.001)
β_{K_M}	0.6234	(0.000)	$\beta_{K_MK_M}$	0.1928	(0.000)
β_{K_B}	0.2625	(0.000)	$\beta_{K_MK_B}$	-0.0579	(0.000)
β_E	-0.0325	(0.077)	β_{K_ME}	-0.1972	(0.000)
$\beta_{K_IK_I}$	-0.0539	(0.000)	$\beta_{K_BK_B}$	0.1039	(0.000)
$\beta_{K_IK_M}$	0.0623	(0.000)	β_{K_BE}	-0.0545	(0.000)
$\beta_{K_IK_B}$	0.0085	(0.022)	β_{EE}	0.2685	(0.000)
Log likelihood		270.6648	Observation		28

[a] K_I: ICT assets, K_M: Machinery, K_B: Buildings; E: Energy aggregate

Table A-I-20. Parameter Estimates of Case 2 (US)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{K_I}	0.1059	(0.000)	β_{K_IE}	0.0137	(0.171)
β_{K_M}	0.5347	(0.000)	$\beta_{K_MK_M}$	0.2305	(0.000)
β_{K_B}	0.3916	(0.000)	$\beta_{K_MK_B}$	-0.0717	(0.000)
β_E	-0.0321	(0.046)	β_{K_ME}	-0.1621	(0.000)
$\beta_{K_IK_I}$	-0.0461	(0.000)	$\beta_{K_BK_B}$	0.1645	(0.000)
$\beta_{K_IK_M}$	0.0033	(0.482)	β_{K_BE}	-0.1220	(0.000)
$\beta_{K_IK_B}$	0.0291	(0.000)	β_{EE}	0.2704	(0.000)
Log likelihood		303.1598	Observation		28

[a] K_I: ICT assets, K_M: Machinery, K_B: Buildings; E: Energy aggregate

3. Case 3: Parameter Estimates of Eq. (I-17)

Table A-I-21. Parameter Estimates of Case 3 (Australia)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_K	0.4228	(0.000)	$\beta_{E_CE_C}$	0.0114	(0.000)
β_{E_C}	0.0357	(0.000)	$\beta_{E_CE_O}$	0.0271	(0.000)
β_{E_O}	0.2087	(0.000)	$\beta_{E_CE_G}$	-0.0187	(0.000)
β_{E_G}	0.1275	(0.000)	$\beta_{E_CE_E}$	-0.0028	(0.537)
β_{E_E}	0.2052	(0.000)	$\beta_{E_OE_O}$	0.1570	(0.009)
β_{KK}	0.2180	(0.000)	$\beta_{E_OE_G}$	0.0010	(0.938)
β_{KE_C}	-0.0170	(0.000)	$\beta_{E_OE_E}$	-0.0992	(0.021)
β_{KE_O}	-0.0859	(0.000)	$\beta_{E_GE_G}$	0.0637	(0.000)
β_{KE_G}	-0.0372	(0.000)	$\beta_{E_GE_E}$	-0.0088	(0.449)
β_{KE_E}	-0.0779	(0.000)	$\beta_{E_EE_E}$	0.1887	(0.000)
Log likelihood		425.5793	Observation		28

[a] K: Capital aggregate; E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-I-22. Parameter Estimates of Case 3 (Austria)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_K	0.5327	(0.000)	$\beta_{E_CE_C}$	-0.0019	(0.887)
β_{E_C}	0.0348	(0.053)	$\beta_{E_CE_O}$	-0.0192	(0.002)
β_{E_O}	-0.0063	(0.722)	$\beta_{E_CE_G}$	0.0299	(0.000)
β_{E_G}	0.1179	(0.000)	$\beta_{E_CE_E}$	0.0133	(0.150)
β_{E_E}	0.3209	(0.000)	$\beta_{E_OE_O}$	-0.0190	(0.007)
β_{KK}	0.1947	(0.000)	$\beta_{E_OE_G}$	0.0154	(0.004)
β_{KE_C}	-0.0221	(0.000)	$\beta_{E_OE_E}$	0.0589	(0.000)
β_{KE_O}	-0.0361	(0.000)	$\beta_{E_GE_G}$	-0.0119	(0.173)
β_{KE_G}	-0.0230	(0.000)	$\beta_{E_GE_E}$	-0.0103	(0.037)
β_{KE_E}	-0.1136	(0.000)	$\beta_{E_EE_E}$	0.0517	(0.000)
Log likelihood		437.2067	Observation		28

[a] K: Capital aggregate; E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-I-23. Parameter Estimates of Case 3 (Denmark)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_K	1.3183	(0.000)	$\beta_{E_CE_C}$	0.0086	(0.000)
β_{E_C}	-0.0337	(0.000)	$\beta_{E_CE_O}$	0.0121	(0.000)
β_{E_O}	-0.0096	(0.768)	$\beta_{E_CE_G}$	-0.0058	(0.013)
β_{E_G}	-0.0845	(0.000)	$\beta_{E_CE_E}$	0.0137	(0.000)
β_{E_E}	-0.1904	(0.000)	$\beta_{E_OE_O}$	0.1787	(0.000)
β_{KK}	0.3141	(0.000)	$\beta_{E_OE_G}$	-0.0769	(0.000)
β_{KE_C}	-0.0286	(0.000)	$\beta_{E_OE_E}$	-0.0097	(0.043)
β_{KE_O}	-0.1043	(0.000)	$\beta_{E_GE_G}$	0.1011	(0.000)
β_{KE_G}	-0.0389	(0.002)	$\beta_{E_GE_E}$	0.0205	(0.000)
β_{KE_E}	-0.1423	(0.000)	$\beta_{E_EE_E}$	0.1178	(0.000)
Log likelihood		344.0947	Observation		24

[a] K: Capital aggregate; E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-I-24. Parameter Estimates of Case 3 (Finland)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_K	0.4776	(0.000)	$\beta_{E_CE_C}$	0.0513	(0.000)
β_{E_C}	0.1158	(0.000)	$\beta_{E_CE_O}$	-0.0194	(0.004)
β_{E_O}	0.2503	(0.000)	$\beta_{E_CE_G}$	0.0021	(0.203)
β_{E_G}	0.0695	(0.000)	$\beta_{E_CE_E}$	-0.0031	(0.680)
β_{E_E}	0.0867	(0.005)	$\beta_{E_OE_O}$	0.2043	(0.000)
β_{KK}	0.2866	(0.000)	$\beta_{E_OE_G}$	0.0016	(0.516)
β_{KE_C}	-0.0310	(0.000)	$\beta_{E_OE_E}$	-0.0292	(0.276)
β_{KE_O}	-0.1573	(0.000)	$\beta_{E_GE_G}$	0.0221	(0.000)
β_{KE_G}	-0.0199	(0.000)	$\beta_{E_GE_E}$	-0.0058	(0.005)
β_{KE_E}	-0.0785	(0.000)	$\beta_{E_EE_E}$	0.1166	(0.000)
Log likelihood		386.9247	Observation		28

[a] K: Capital aggregate; E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-I-25. Parameter Estimates of Case 3 (Italy)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_K	0.3786	(0.000)	$\beta_{E_CE_C}$	0.0033	(0.006)
β_{E_C}	0.0162	(0.000)	$\beta_{E_CE_O}$	0.0029	(0.125)
β_{E_O}	0.3306	(0.000)	$\beta_{E_CE_G}$	-0.0017	(0.514)
β_{E_G}	0.0447	(0.019)	$\beta_{E_CE_E}$	0.0034	(0.003)
β_{E_E}	0.2298	(0.000)	$\beta_{E_OE_O}$	0.2066	(0.000)
β_{KK}	0.2982	(0.000)	$\beta_{E_OE_G}$	-0.0086	(0.173)
β_{KE_C}	-0.0079	(0.000)	$\beta_{E_OE_E}$	-0.0336	(0.0000
β_{KE_O}	-0.1673	(0.000)	$\beta_{E_GE_G}$	0.0126	(0.265)
β_{KE_G}	-0.0071	(0.014)	$\beta_{E_GE_E}$	0.0048	(0.214)
β_{KE_E}	-0.1159	(0.000)	$\beta_{E_EE_E}$	0.1414	(0.000)
Log likelihood		487.4775	Observation		28

[a] K: Capital aggregate; E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-I-26. Parameter Estimates of Case 3 (Japan)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_K	0.9045	(0.000)	$\beta_{E_CE_C}$	0.0090	(0.000)
β_{E_C}	0.0301	(0.000)	$\beta_{E_CE_O}$	-0.0000	(0.950)
β_{E_O}	0.1378	(0.000)	$\beta_{E_CE_G}$	0.0009	(0.071)
β_{E_G}	-0.0105	(0.012)	$\beta_{E_CE_E}$	-0.0090	(0.000)
β_{E_E}	-0.0619	(0.392)	$\beta_{E_OE_O}$	0.0226	(0.000)
β_{KK}	0.0193	(0.279)	$\beta_{E_OE_G}$	0.0003	(0.360)
β_{KE_C}	-0.0008	(0.435)	$\beta_{E_OE_E}$	-0.0343	(0.000)
β_{KE_O}	0.0115	(0.043)	$\beta_{E_GE_G}$	0.0075	(0.000)
β_{KE_G}	-0.0051	(0.000)	$\beta_{E_GE_E}$	-0.0037	(0.005)
β_{KE_E}	-0.0248	(0.057)	$\beta_{E_EE_E}$	0.0717	(0.000)
Log likelihood		506.4912	Observation		27

[a] K: Capital aggregate; E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-I-27. Parameter Estimates of Case 3 (Korea)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_K	2.1872	(0.000)	$\beta_{E_CE_C}$	-0.0012	(0.192)
β_{E_C}	0.0025	(0.619)	$\beta_{E_CE_O}$	0.0011	(0.332)
β_{E_O}	-0.0526	(0.215)	$\beta_{E_CE_G}$	0.0004	(0.765)
β_{E_G}	-0.0244	(0.283)	$\beta_{E_CE_E}$	0.0000	(0.963)
β_{E_E}	-1.1127	(0.000)	$\beta_{E_OE_O}$	-0.0291	(0.004)
β_{KK}	0.2289	(0.000)	$\beta_{E_OE_G}$	0.0063	(0.351)
β_{KE_C}	-0.0004	(0.643)	$\beta_{E_OE_E}$	0.0480	(0.000)
β_{KE_O}	-0.0264	(0.000)	$\beta_{E_GE_G}$	0.0290	(0.000)
β_{KE_G}	-0.0120	(0.001)	$\beta_{E_GE_E}$	-0.0236	(0.000)
β_{KE_E}	-0.1901	(0.000)	$\beta_{E_EE_E}$	0.1657	(0.000)
Log likelihood		369.0930	Observation		23

[a] K: Capital aggregate; E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-I-28. Parameter Estimates of Case 3 (Netherlands)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_K	0.5103	(0.000)	$\beta_{E_CE_C}$	0.0216	(0.000)
β_{E_C}	0.0474	(0.000)	$\beta_{E_CE_O}$	-0.0003	(0.901)
β_{E_O}	0.0926	(0.000)	$\beta_{E_CE_G}$	-0.0023	(0.521)
β_{E_G}	0.2781	(0.000)	$\beta_{E_CE_E}$	-0.0137	(0.000)
β_{E_E}	0.0717	(0.000)	$\beta_{E_OE_O}$	0.0196	(0.197)
β_{KK}	0.3300	(0.000)	$\beta_{E_OE_G}$	0.0567	(0.000)
β_{KE_C}	-0.0053	(0.010)	$\beta_{E_OE_E}$	0.0024	(0.683)
β_{KE_O}	-0.0784	(0.000)	$\beta_{E_GE_G}$	0.1431	(0.000)
β_{KE_G}	-0.1454	(0.000)	$\beta_{E_GE_E}$	-0.0521	(0.000)
β_{KE_E}	-0.1009	(0.000)	$\beta_{E_EE_E}$	0.1643	(0.000)
Log likelihood		422.2720	Observation		28

[a] K: Capital aggregate; E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-I-29. Parameter Estimates of Case 3 (UK)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_K	0.4913	(0.000)	$\beta_{E_CE_C}$	0.0387	(0.000)
β_{E_C}	0.0669	(0.000)	$\beta_{E_CE_O}$	-0.0174	(0.000)
β_{E_O}	0.1255	(0.000)	$\beta_{E_CE_G}$	0.0021	(0.540)
β_{E_G}	0.1736	(0.000)	$\beta_{E_CE_E}$	0.0127	(0.002)
β_{E_E}	0.1427	(0.000)	$\beta_{E_OE_O}$	0.0758	(0.000)
β_{KK}	0.2399	(0.000)	$\beta_{E_OE_G}$	0.0285	(0.000)
β_{KE_C}	-0.0361	(0.000)	$\beta_{E_OE_E}$	-0.0403	(0.000)
β_{KE_O}	-0.0467	(0.000)	$\beta_{E_GE_G}$	0.0562	(0.000)
β_{KE_G}	-0.0620	(0.000)	$\beta_{E_GE_E}$	-0.0248	(0.000)
β_{KE_E}	-0.0951	(0.000)	$\beta_{E_EE_E}$	0.1475	(0.000)
Log likelihood		393.4232	Observation		28

[a] K: Capital aggregate; E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-I-30. Parameter Estimates of Case 3 (US)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_K	0.5064	(0.000)	$\beta_{E_C E_C}$	0.0208	(0.000)
β_{E_C}	0.0610	(0.000)	$\beta_{E_C E_O}$	-0.0008	(0.630)
β_{E_O}	0.1414	(0.000)	$\beta_{E_C E_G}$	0.0110	(0.000)
β_{E_G}	0.2208	(0.000)	$\beta_{E_C E_E}$	-0.0150	(0.000)
β_{E_E}	0.0703	(0.000)	$\beta_{E_O E_O}$	0.1239	(0.000)
β_{KK}	0.3314	(0.000)	$\beta_{E_O E_G}$	0.0116	(0.010)
β_{KE_C}	-0.0160	(0.000)	$\beta_{E_O E_E}$	-0.0302	(0.000)
β_{KE_O}	-0.1045	(0.000)	$\beta_{E_G E_G}$	0.2208	(0.000)
β_{KE_G}	-0.1094	(0.000)	$\beta_{E_G E_E}$	-0.0260	(0.000)
β_{KE_E}	-0.1015	(0.000)	$\beta_{E_E E_E}$	0.1727	(0.000)
Log likelihood		378.5768	Observation		28

[a] K: Capital aggregate; E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

APPENDIX II

1. Extended Energy Sub-Model

1. 1. ICT Assets (K_1)

Table A-II-1. Parameter Estimates (Australia)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.059	(0.000)	$\beta_{E_O E_G}$	0.033	(0.277)
β_{E_O}	0.235	(0.000)	$\beta_{E_O E_E}$	0.132	(0.422)
β_{E_G}	0.181	(0.000)	$\beta_{E_G E_G}$	0.115	(0.000)
β_{E_E}	0.525	(0.000)	$\beta_{E_G E_E}$	-0.126	(0.000)
$\beta_{E_C E_C}$	0.056	(0.000)	$\beta_{E_E E_E}$	0.016	(0.912)
$\beta_{E_C E_O}$	-0.011	(0.310)	α_{E_C}	-0.268	(0.0000
$\beta_{E_C E_G}$	-0.023	(0.000)	α_{E_O}	-1.509	(0.000)
$\beta_{E_C E_E}$	-0.022	(0.005)	α_{E_G}	0.276	(0.000)
$\beta_{E_O E_O}$	-0.154	(0.399)	α_{E_E}	1.501	(0.000)
Log likelihood		268.6077	LR statistic ($\forall \alpha_{E_i} = 0$)		37.023

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-2. Parameter Estimates (Austria)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.055	(0.000)	$\beta_{E_O E_G}$	0.039	(0.001)
β_{E_O}	0.081	(0.000)	$\beta_{E_O E_E}$	-0.067	(0.005)
β_{E_G}	0.161	(0.000)	$\beta_{E_G E_G}$	-0.035	(0.086)
β_{E_E}	0.704	(0.000)	$\beta_{E_G E_E}$	-0.015	(0.375)
$\beta_{E_C E_C}$	0.119	(0.000)	$\beta_{E_E E_E}$	0.200	(0.000)
$\beta_{E_C E_O}$	-0.011	(0.444)	α_{E_C}	-0.539	(0.000)
$\beta_{E_C E_G}$	0.011	(0.567)	α_{E_O}	-0.920	(0.000)
$\beta_{E_C E_E}$	-0.119	(0.000)	α_{E_G}	0.890	(0.000)
$\beta_{E_O E_O}$	0.039	(0.092)	α_{E_E}	0.568	(0.000)
Log likelihood		272.8102	LR statistic ($\forall \alpha_{E_i} = 0$)		83.691

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-3. Parameter Estimates (Denmark)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.048	(0.000)	$\beta_{E_O E_G}$	-0.302	(0.000)
β_{E_O}	0.294	(0.000)	$\beta_{E_O E_E}$	-0.097	(0.000)
β_{E_G}	0.205	(0.000)	$\beta_{E_G E_G}$	0.421	(0.000)
β_{E_E}	0.453	(0.000)	$\beta_{E_G E_E}$	-0.117	(0.000)
$\beta_{E_C E_C}$	0.044	(0.000)	$\beta_{E_E E_E}$	0.243	(0.000)
$\beta_{E_C E_O}$	-0.014	(0.016)	α_{E_C}	-0.104	(0.003)
$\beta_{E_C E_G}$	-0.002	(0.721)	α_{E_O}	-1.764	(0.000)
$\beta_{E_C E_E}$	-0.028	(0.000)	α_{E_G}	1.399	(0.000)
$\beta_{E_O E_O}$	0.413	(0.000)	α_{E_E}	0.469	(0.000)
Log likelihood		218.9318	LR statistic ($\forall \alpha_{E_i} = 0$)		55.273

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-4. Parameter Estimates (Finland)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.126	(0.000)	$\beta_{E_O E_G}$	-0.012	(0.582)
β_{E_O}	0.361	(0.000)	$\beta_{E_O E_E}$	-0.041	(0.713)
β_{E_G}	0.081	(0.000)	$\beta_{E_G E_G}$	0.075	(0.000)
β_{E_E}	0.433	(0.000)	$\beta_{E_G E_E}$	-0.050	(0.008)
$\beta_{E_C E_C}$	0.164	(0.000)	$\beta_{E_E E_E}$	0.167	(0.069)
$\beta_{E_C E_O}$	-0.075	(0.002)	α_{E_C}	-0.208	(0.125)
$\beta_{E_C E_G}$	-0.013	(0.038)	α_{E_O}	-1.864	(0.078)
$\beta_{E_C E_E}$	-0.076	(0.001)	α_{E_G}	0.367	(0.052)
$\beta_{E_O E_O}$	0.129	(0.335)	α_{E_E}	1.705	(0.064)
Log likelihood		244.3992	LR statistic ($\forall \alpha_{E_i} = 0$)		6.206

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-5. Parameter Estimates (Italy)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.029	(0.000)	$\beta_{E_O E_G}$	-0.059	(0.00)
β_{E_O}	0.450	(0.000)	$\beta_{E_O E_E}$	-0.341	(0.000)
β_{E_G}	0.031	(0.000)	$\beta_{E_G E_G}$	0.024	(0.486)
β_{E_E}	0.490	(0.000)	$\beta_{E_G E_E}$	0.030	(0.072)
$\beta_{E_C E_C}$	0.010	(0.005)	$\beta_{E_E E_E}$	0.321	(0.000)
$\beta_{E_C E_O}$	-0.006	(0.276)	α_{E_C}	-0.490	(0.000)
$\beta_{E_C E_G}$	0.006	(0.490)	α_{E_O}	-10.848	(0.000)
$\beta_{E_C E_E}$	-0.010	(0.007)	α_{E_G}	2.748	(0.000)
$\beta_{E_O E_O}$	0.406	(0.000)	α_{E_E}	8.590	(0.000)
Log likelihood		292.1909	LR statistic ($\forall \alpha_{E_i} = 0$)		70.403

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-6. Parameter Estimates (Japan)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.048	(0.000)	$\beta_{E_O E_G}$	-0.003	(0.133)
β_{E_O}	0.202	(0.000)	$\beta_{E_O E_E}$	-0.150	(0.000)
β_{E_G}	0.021	(0.000)	$\beta_{E_G E_G}$	0.029	(0.000)
β_{E_E}	0.728	(0.000)	$\beta_{E_G E_E}$	-0.033	(0.000)
$\beta_{E_C E_C}$	0.052	(0.000)	$\beta_{E_E E_E}$	0.242	(0.000)
$\beta_{E_C E_O}$	-0.000	(0.885)	α_{E_C}	-0.056	(0.386)
$\beta_{E_C E_G}$	0.006	(0.049)	α_{E_O}	-1.608	(0.000)
$\beta_{E_C E_E}$	-0.059	(0.000)	α_{E_G}	0.398	(0.000)
$\beta_{E_O E_O}$	0.154	(0.000)	α_{E_E}	1.266	(0.000)
Log likelihood		329.0301	LR statistic ($\forall \alpha_{E_i} = 0$)		68.877

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-7. Parameter Estimates (Korea)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.022	(0.000)	$\beta_{E_O E_G}$	0.008	(0.496)
β_{E_O}	0.530	(0.000)	$\beta_{E_O E_E}$	-0.062	(0.009)
β_{E_G}	-0.038	(0.000)	$\beta_{E_G E_G}$	0.032	(0.023)
β_{E_E}	0.486	(0.000)	$\beta_{E_G E_E}$	-0.040	(0.000)
$\beta_{E_C E_C}$	0.017	(0.000)	$\beta_{E_E E_E}$	0.119	(0.000)
$\beta_{E_C E_O}$	-0.000	(0.884)	α_{E_C}	-0.154	(0.285)
$\beta_{E_C E_G}$	0.000	(0.948)	α_{E_O}	-6.381	(0.000)
$\beta_{E_C E_E}$	-0.017	(0.001)	α_{E_G}	1.394	(0.000)
$\beta_{E_O E_O}$	0.054	(0.053)	α_{E_E}	5.141	(0.000)
Log likelihood		265.5130	LR statistic ($\forall \alpha_{E_i} = 0$)		22.246

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-8. Parameter Estimates (Netherlands)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.029	(0.000)	$\beta_{E_O E_G}$	0.038	(0.002)
β_{E_O}	0.134	(0.000)	$\beta_{E_O E_E}$	0.074	(0.023)
β_{E_G}	0.362	(0.000)	$\beta_{E_G E_G}$	0.166	(0.000)
β_{E_E}	0.475	(0.000)	$\beta_{E_G E_E}$	-0.199	(0.000)
$\beta_{E_C E_C}$	0.039	(0.000)	$\beta_{E_E E_E}$	0.159	(0.000)
$\beta_{E_C E_O}$	0.002	(0.771)	α_{E_C}	-0.080	(0.316)
$\beta_{E_C E_G}$	-0.005	(0.533)	α_{E_O}	-0.890	(0.009)
$\beta_{E_C E_E}$	-0.035	(0.000)	α_{E_G}	-1.215	(0.000)
$\beta_{E_O E_O}$	-0.114	(0.006)	α_{E_E}	2.185	(0.000)
Log likelihood		275.8090	LR statistic ($\forall \alpha_{E_i} = 0$)		90.103

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-9. Parameter Estimates (UK)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.105	(0.000)	$\beta_{E_O E_G}$	0.061	(0.000)
β_{E_O}	0.169	(0.000)	$\beta_{E_O E_E}$	-0.152	(0.000)
β_{E_G}	0.237	(0.000)	$\beta_{E_G E_G}$	0.110	(0.000)
β_{E_E}	0.488	(0.000)	$\beta_{E_G E_E}$	-0.158	(0.000)
$\beta_{E_C E_C}$	0.115	(0.000)	$\beta_{E_E E_E}$	0.369	(0.000)
$\beta_{E_C E_O}$	-0.043	(0.000)	α_{E_C}	-0.171	(0.341)
$\beta_{E_C E_G}$	-0.013	(0.308)	α_{E_O}	-1.132	(0.000)
$\beta_{E_C E_E}$	-0.058	(0.000)	α_{E_G}	-0.550	(0.000)
$\beta_{E_O E_O}$	0.135	(0.000)	α_{E_E}	1.853	(0.000)
Log likelihood		251.2982	LR statistic ($\forall \alpha_{E_i} = 0$)		52.366

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-10. Parameter Estimates (US)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.040	(0.000)	$\beta_{E_O E_G}$	-0.054	(0.000)
β_{E_O}	0.196	(0.000)	$\beta_{E_O E_E}$	-0.133	(0.000)
β_{E_G}	0.243	(0.000)	$\beta_{E_G E_G}$	0.257	(0.000)
β_{E_E}	0.521	(0.000)	$\beta_{E_G E_E}$	-0.212	(0.000)
$\beta_{E_C E_C}$	0.051	(0.000)	$\beta_{E_E E_E}$	0.389	(0.000)
$\beta_{E_C E_O}$	-0.016	(0.000)	α_{E_C}	-0.106	(0.094)
$\beta_{E_C E_G}$	0.009	(0.002)	α_{E_O}	-0.970	(0.000)
$\beta_{E_C E_E}$	-0.045	(0.000)	α_{E_G}	-0.017	(0.794)
$\beta_{E_O E_O}$	0.202	(0.000)	α_{E_E}	1.094	(0.000)
Log likelihood		265.1970	LR statistic ($\forall \alpha_{E_i} = 0$)		50.492

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

1. 2. Transport equipment (K_2)

Table A-II-11. Parameter Estimates (Australia)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	-0.013	(0.497)	$\beta_{E_O E_G}$	0.007	(0.886)
β_{E_O}	-0.117	(0.390)	$\beta_{E_O E_E}$	-0.086	(0.787)
β_{E_G}	0.261	(0.000)	$\beta_{E_G E_G}$	0.118	(0.000)
β_{E_E}	0.869	(0.000)	$\beta_{E_G E_E}$	-0.088	(0.118)
$\beta_{E_C E_C}$	0.037	(0.000)	$\beta_{E_E E_E}$	0.178	(0.546)
$\beta_{E_C E_O}$	0.003	(0.938)	α_{E_C}	0.903	(0.000)
$\beta_{E_C E_G}$	-0.036	(0.000)	α_{E_O}	4.325	(0.012)
$\beta_{E_C E_E}$	-0.003	(0.912)	α_{E_G}	-0.988	(0.000)
$\beta_{E_O E_O}$	0.076	(0.816)	α_{E_E}	-4.240	(0.017)
Log likelihood		254.8219	LR statistic ($\forall \alpha_{E_i} = 0$)		9.451

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-12. Parameter Estimates (Austria)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	-0.110	(0.000)	$\beta_{E_O E_G}$	0.106	(0.000)
β_{E_O}	-0.215	(0.000)	$\beta_{E_O E_E}$	-0.023	(0.204)
β_{E_G}	0.423	(0.000)	$\beta_{E_G E_G}$	-0.131	(0.000)
β_{E_E}	0.902	(0.000)	$\beta_{E_G E_E}$	-0.058	(0.002)
$\beta_{E_C E_C}$	0.064	(0.140)	$\beta_{E_E E_E}$	0.170	(0.000)
$\beta_{E_C E_O}$	-0.057	(0.000)	α_{E_C}	6.201	(0.000)
$\beta_{E_C E_G}$	0.083	(0.004)	α_{E_O}	11.320	(0.000)
$\beta_{E_C E_E}$	-0.090	(0.000)	α_{E_G}	-9.877	(0.000)
$\beta_{E_O E_O}$	-0.026	(0.092)	α_{E_E}	-7.645	(0.000)
Log likelihood		263.3090	LR statistic ($\forall \alpha_{E_i} = 0$)		64.689

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-13. Parameter Estimates (Denmark)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.071	(0.015)	$\beta_{E_O E_G}$	-0.428	(0.000)
β_{E_O}	-0.897	(0.000)	$\beta_{E_O E_E}$	-0.098	(0.000)
β_{E_G}	1.201	(0.000)	$\beta_{E_G E_G}$	0.547	(0.000)
β_{E_E}	0.624	(0.000)	$\beta_{E_G E_E}$	-0.146	(0.000)
$\beta_{E_C E_C}$	0.051	(0.000)	$\beta_{E_E E_E}$	0.296	(0.000)
$\beta_{E_C E_O}$	-0.027	(0.012)	α_{E_C}	-0.873	(0.376)
$\beta_{E_C E_G}$	0.027	(0.004)	α_{E_O}	36.694	(0.000)
$\beta_{E_C E_E}$	-0.051	(0.000)	α_{E_G}	-30.738	(0.000)
$\beta_{E_O E_O}$	0.553	(0.000)	α_{E_E}	-5.083	(0.002)
Log likelihood		204.6045	LR statistic ($\forall \alpha_{E_i} = 0$)		26.619

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-14. Parameter Estimates (Finland)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.085	(0.000)	$\beta_{E_O E_G}$	-0.072	(0.000)
β_{E_O}	-0.103	(0.054)	$\beta_{E_O E_E}$	-0.339	(0.000)
β_{E_G}	0.168	(0.000)	$\beta_{E_G E_G}$	0.086	(0.000)
β_{E_E}	0.850	(0.000)	$\beta_{E_G E_E}$	0.002	(0.895)
$\beta_{E_C E_C}$	0.134	(0.000)	$\beta_{E_E E_E}$	0.408	(0.000)
$\beta_{E_C E_O}$	-0.047	(0.061)	α_{E_C}	1.221	(0.004)
$\beta_{E_C E_G}$	-0.016	(0.002)	α_{E_O}	13.762	(0.000)
$\beta_{E_C E_E}$	-0.070	(0.000)	α_{E_G}	-2.579	(0.000)
$\beta_{E_O E_O}$	0.458	(0.000)	α_{E_E}	-12.404	(0.000)
Log likelihood		267.3175	LR statistic ($\forall \alpha_{E_i} = 0$)		52.043

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-15. Parameter Estimates (Italy)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	-0.011	(0.109)	$\beta_{E_O E_G}$	-0.060	(0.000)
β_{E_O}	-0.671	(0.000)	$\beta_{E_O E_E}$	-0.254	(0.000)
β_{E_G}	0.301	(0.000)	$\beta_{E_G E_G}$	0.072	(0.001)
β_{E_E}	1.382	(0.000)	$\beta_{E_G E_E}$	0.000	(0.975)
$\beta_{E_C E_C}$	0.014	(0.000)	$\beta_{E_E E_E}$	0.252	(0.000)
$\beta_{E_C E_O}$	-0.002	(0.726)	α_{E_C}	1.125	(0.000)
$\beta_{E_C E_G}$	-0.013	(0.134)	α_{E_O}	33.436	(0.000)
$\beta_{E_C E_E}$	0.001	(0.812)	α_{E_G}	-7.918	(0.000)
$\beta_{E_O E_O}$	0.316	(0.000)	α_{E_E}	-26.643	(0.000)
Log likelihood		276.5396	LR statistic ($\forall \alpha_{E_i} = 0$)		39.101

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-16. Parameter Estimates (Japan)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.034	(0.000)	$\beta_{E_O E_G}$	-0.021	(0.014)
β_{E_O}	0.240	(0.000)	$\beta_{E_O E_E}$	-0.169	(0.000)
β_{E_G}	0.004	(0.627)	$\beta_{E_G E_G}$	0.046	(0.000)
β_{E_E}	0.722	(0.000)	$\beta_{E_G E_E}$	-0.030	(0.013)
$\beta_{E_C E_C}$	0.043	(0.000)	$\beta_{E_E E_E}$	0.238	(0.000)
$\beta_{E_C E_O}$	-0.011	(0.138)	α_{E_C}	0.699	(0.118)
$\beta_{E_C E_G}$	0.006	(0.067)	α_{E_O}	-4.519	(0.007)
$\beta_{E_C E_E}$	-0.038	(0.000)	α_{E_G}	1.535	(0.001)
$\beta_{E_O E_O}$	0.201	(0.000)	α_{E_E}	2.285	(0.059)
Log likelihood		299.0916	LR statistic ($\forall \alpha_{E_i} = 0$)		9.000

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-17. Parameter Estimates (Korea)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.032	(0.150)	$\beta_{E_O E_G}$	0.038	(0.191)
β_{E_O}	0.245	(0.366)	$\beta_{E_O E_E}$	0.054	(0.457)
β_{E_G}	0.049	(0.488)	$\beta_{E_G E_G}$	0.018	(0.281)
β_{E_E}	0.674	(0.003)	$\beta_{E_G E_E}$	-0.061	(0.003)
$\beta_{E_C E_C}$	0.020	(0.000)	$\beta_{E_E E_E}$	0.020	(0.742)
$\beta_{E_C E_O}$	-0.013	(0.121)	α_{E_C}	-0.157	(0.575)
$\beta_{E_C E_G}$	0.005	(0.179)	α_{E_O}	1.519	(0.657)
$\beta_{E_C E_E}$	-0.013	(0.040)	α_{E_G}	-0.637	(0.476)
$\beta_{E_O E_O}$	-0.078	(0.387)	α_{E_E}	-0.725	(0.803)
Log likelihood		255.7684	LR statistic ($\forall \alpha_{E_i} = 0$)		2.757

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-18. Parameter Estimates (Netherlands)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.030	(0.000)	$\beta_{E_O E_G}$	0.080	(0.006)
β_{E_O}	-0.102	(0.132)	$\beta_{E_O E_E}$	-0.031	(0.375)
β_{E_G}	0.186	(0.000)	$\beta_{E_G E_G}$	0.092	(0.004)
β_{E_E}	0.886	(0.000)	$\beta_{E_G E_E}$	-0.159	(0.000)
$\beta_{E_C E_C}$	0.049	(0.000)	$\beta_{E_E E_E}$	0.225	(0.000)
$\beta_{E_C E_O}$	-0.001	(0.896)	α_{E_C}	-0.206	(0.575)
$\beta_{E_C E_G}$	-0.013	(0.026)	α_{E_O}	11.031	(0.004)
$\beta_{E_C E_E}$	-0.035	(0.000)	α_{E_G}	6.705	(0.000)
$\beta_{E_O E_O}$	-0.048	(0.138)	α_{E_E}	-17.530	(0.000)
Log likelihood		240.7731	LR statistic ($\forall \alpha_{E_i} = 0$)		20.031

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-19. Parameter Estimates (UK)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.063	(0.002)	$\beta_{E_O E_G}$	0.046	(0.000)
β_{E_O}	0.008	(0.677)	$\beta_{E_O E_E}$	-0.127	(0.000)
β_{E_G}	0.191	(0.000)	$\beta_{E_G E_G}$	0.093	(0.000)
β_{E_E}	0.738	(0.000)	$\beta_{E_G E_E}$	-0.140	(0.000)
$\beta_{E_C E_C}$	0.083	(0.000)	$\beta_{E_E E_E}$	0.295	(0.000)
$\beta_{E_C E_O}$	-0.056	(0.000)	α_{E_C}	0.698	(0.067)
$\beta_{E_C E_G}$	0.001	(0.899)	α_{E_O}	2.299	(0.000)
$\beta_{E_C E_E}$	-0.028	(0.012)	α_{E_G}	0.549	(0.000)
$\beta_{E_O E_O}$	0.137	(0.000)	α_{E_E}	-3.546	(0.000)
Log likelihood		264.0557	LR statistic ($\forall \alpha_{E_i} = 0$)		77.881

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-20. Parameter Estimates (US)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.080	(0.000)	$\beta_{E_O E_G}$	-0.055	(0.000)
β_{E_O}	-0.204	(0.000)	$\beta_{E_O E_E}$	-0.132	(0.000)
β_{E_G}	0.209	(0.000)	$\beta_{E_G E_G}$	0.262	(0.000)
β_{E_E}	0.915	(0.000)	$\beta_{E_G E_E}$	-0.206	(0.000)
$\beta_{E_C E_C}$	0.098	(0.000)	$\beta_{E_E E_E}$	0.414	(0.000)
$\beta_{E_C E_O}$	-0.022	(0.000)	α_{E_C}	-1.176	(0.009)
$\beta_{E_C E_G}$	-0.001	(0.855)	α_{E_O}	8.771	(0.000)
$\beta_{E_C E_E}$	-0.075	(0.000)	α_{E_G}	0.828	(0.215)
$\beta_{E_O E_O}$	0.208	(0.000)	α_{E_E}	-8.423	(0.000)
Log likelihood		261.7831	LR statistic ($\forall \alpha_{E_i} = 0$)		43.665

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

1. 3. Other Machinery (K_3)

Table A-II-21. Parameter Estimates (Australia)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.051	(0.528)	$\beta_{E_O E_G}$	-0.067	(0.236)
β_{E_O}	0.234	(0.646)	$\beta_{E_O E_E}$	-0.396	(0.190)
β_{E_G}	0.174	(0.055)	$\beta_{E_G E_G}$	0.146	(0.000)
β_{E_E}	0.540	(0.279)	$\beta_{E_G E_E}$	-0.032	(0.617)
$\beta_{E_C E_C}$	0.025	(0.000)	$\beta_{E_E E_E}$	0.475	(0.082)
$\beta_{E_C E_O}$	0.067	(0.130)	α_{E_C}	0.006	(0.971)
$\beta_{E_C E_G}$	-0.046	(0.001)	α_{E_O}	-0.080	(0.936)
$\beta_{E_C E_E}$	-0.047	(0.178)	α_{E_G}	0.030	(0.869)
$\beta_{E_O E_O}$	0.396	(0.207)	α_{E_E}	0.044	(0.964)
Log likelihood		250.1077	LR statistic ($\forall \alpha_{E_i} = 0$)		0.022

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-22. Parameter Estimates (Austria)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	-0.356	(0.000)	$\beta_{E_O E_G}$	-0.055	(0.117)
β_{E_O}	-0.435	(0.000)	$\beta_{E_O E_E}$	-0.153	(0.000)
β_{E_G}	0.901	(0.000)	$\beta_{E_G E_G}$	-0.058	(0.042)
β_{E_E}	0.889	(0.000)	$\beta_{E_G E_E}$	0.112	(0.003)
$\beta_{E_C E_C}$	0.144	(0.000)	$\beta_{E_E E_E}$	0.233	(0.000)
$\beta_{E_C E_O}$	0.047	(0.037)	α_{E_C}	0.803	(0.000)
$\beta_{E_C E_G}$	0.001	(0.972)	α_{E_O}	1.005	(0.000)
$\beta_{E_C E_E}$	-0.192	(0.000)	α_{E_G}	-1.448	(0.000)
$\beta_{E_O E_O}$	0.160	(0.002)	α_{E_E}	-0.359	(0.091)
Log likelihood		248.5283	LR statistic ($\forall \alpha_{E_i} = 0$)		35.127

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-23. Parameter Estimates (Denmark)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	-0.034	(0.223)	$\beta_{E_O E_G}$	-0.352	(0.000)
β_{E_O}	-1.273	(0.000)	$\beta_{E_O E_E}$	-0.116	(0.000)
β_{E_G}	1.394	(0.000)	$\beta_{E_G E_G}$	0.446	(0.000)
β_{E_E}	0.912	(0.000)	$\beta_{E_G E_E}$	-0.096	(0.000)
$\beta_{E_C E_C}$	0.038	(0.000)	$\beta_{E_E E_E}$	0.244	(0.000)
$\beta_{E_C E_O}$	-0.008	(0.232)	α_{E_C}	0.164	(0.005)
$\beta_{E_C E_G}$	0.002	(0.786)	α_{E_O}	3.131	(0.000)
$\beta_{E_C E_E}$	-0.031	(0.000)	α_{E_G}	-2.372	(0.000)
$\beta_{E_O E_O}$	0.476	(0.000)	α_{E_E}	-0.923	(0.000)
Log likelihood		217.8420	LR statistic ($\forall \alpha_{E_i} = 0$)		53.094

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-24. Parameter Estimates (Finland)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.143	(0.014)	$\beta_{E_O E_G}$	-0.011	(0.111)
β_{E_O}	2.566	(0.000)	$\beta_{E_O E_E}$	-0.034	(0.288)
β_{E_G}	-0.295	(0.000)	$\beta_{E_G E_G}$	0.072	(0.000)
β_{E_E}	-1.413	(0.000)	$\beta_{E_G E_E}$	-0.051	(0.000)
$\beta_{E_C E_C}$	0.192	(0.000)	$\beta_{E_E E_E}$	0.166	(0.000)
$\beta_{E_C E_O}$	-0.101	(0.000)	α_{E_C}	-0.052	(0.669)
$\beta_{E_C E_G}$	-0.010	(0.029)	α_{E_O}	-4.868	(0.000)
$\beta_{E_C E_E}$	-0.082	(0.000)	α_{E_G}	0.835	(0.000)
$\beta_{E_O E_O}$	0.146	(0.000)	α_{E_E}	4.085	(0.000)
Log likelihood		271.6097	LR statistic ($\forall \alpha_{E_i} = 0$)		60.627

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-25. Parameter Estimates (Italy)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.155	(0.000)	$\beta_{E_O E_G}$	0.039	(0.013)
β_{E_O}	4.922	(0.000)	$\beta_{E_O E_E}$	0.289	(0.017)
β_{E_G}	-1.000	(0.000)	$\beta_{E_G E_G}$	0.128	(0.000)
β_{E_E}	-3.077	(0.006)	$\beta_{E_G E_E}$	-0.150	(0.000)
$\beta_{E_C E_C}$	0.014	(0.000)	$\beta_{E_E E_E}$	-0.158	(0.164)
$\beta_{E_C E_O}$	-0.017	(0.002)	α_{E_C}	-0.271	(0.000)
$\beta_{E_C E_G}$	-0.016	(0.044)	α_{E_O}	-9.362	(0.000)
$\beta_{E_C E_E}$	0.019	(0.000)	α_{E_G}	2.168	(0.000)
$\beta_{E_O E_O}$	-0.310	(0.018)	α_{E_E}	7.466	(0.001)
Log likelihood		275.2767	LR statistic ($\forall \alpha_{E_i} = 0$)		36.575

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-26. Parameter Estimates (Japan)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.054	(0.004)	$\beta_{E_O E_G}$	0.002	(0.245)
β_{E_O}	0.540	(0.000)	$\beta_{E_O E_E}$	-0.134	(0.000)
β_{E_G}	-0.064	(0.000)	$\beta_{E_G E_G}$	0.025	(0.000)
β_{E_E}	0.470	(0.000)	$\beta_{E_G E_E}$	-0.034	(0.000)
$\beta_{E_C E_C}$	0.051	(0.000)	$\beta_{E_E E_E}$	0.225	(0.000)
$\beta_{E_C E_O}$	-0.001	(0.735)	α_{E_C}	-0.020	(0.706)
$\beta_{E_C E_G}$	0.007	(0.014)	α_{E_O}	-1.072	(0.000)
$\beta_{E_C E_E}$	-0.057	(0.000)	α_{E_G}	0.269	(0.000)
$\beta_{E_O E_O}$	0.133	(0.000)	α_{E_E}	0.822	(0.000)
Log likelihood		318.7225	LR statistic ($\forall \alpha_{E_i} = 0$)		48.262

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-27. Parameter Estimates (Korea)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.022	(0.323)	$\beta_{E_O E_G}$	0.046	(0.000)
β_{E_O}	0.931	(0.003)	$\beta_{E_O E_E}$	0.077	(0.000)
β_{E_G}	-0.197	(0.001)	$\beta_{E_G E_G}$	0.025	(0.062)
β_{E_E}	0.244	(0.371)	$\beta_{E_G E_E}$	-0.070	(0.000)
$\beta_{E_C E_C}$	0.014	(0.000)	$\beta_{E_E E_E}$	0.004	(0.694)
$\beta_{E_C E_O}$	-0.002	(0.342)	α_{E_C}	-0.008	(0.849)
$\beta_{E_C E_G}$	-0.001	(0.603)	α_{E_O}	-1.045	(0.066)
$\beta_{E_C E_E}$	-0.011	(0.000)	α_{E_G}	0.360	(0.002)
$\beta_{E_O E_O}$	-0.122	(0.000)	α_{E_E}	0.692	(0.168)
Log likelihood		258.5589	LR statistic ($\forall \alpha_{E_i} = 0$)		8.338

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-28. Parameter Estimates (Netherlands)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	-0.018	(0.607)	$\beta_{E_O E_G}$	0.076	(0.003)
β_{E_O}	1.035	(0.000)	$\beta_{E_O E_E}$	-0.061	(0.011)
β_{E_G}	0.593	(0.000)	$\beta_{E_G E_G}$	0.067	(0.048)
β_{E_E}	-0.611	(0.000)	$\beta_{E_G E_E}$	-0.127	(0.000)
$\beta_{E_C E_C}$	0.054	(0.000)	$\beta_{E_E E_E}$	0.220	(0.0000
$\beta_{E_C E_O}$	-0.005	(0.416)	α_{E_C}	0.097	(0.203)
$\beta_{E_C E_G}$	-0.016	(0.019)	α_{E_O}	-2.043	(0.000)
$\beta_{E_C E_E}$	-0.032	(0.000)	α_{E_G}	-0.624	(0.001)
$\beta_{E_O E_O}$	-0.010	(0.650)	α_{E_E}	2.570	(0.000)
Log likelihood		255.3136	LR statistic ($\forall \alpha_{E_i} = 0$)		49.112

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-29. Parameter Estimates (UK)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.144	(0.422)	$\beta_{E_O E_G}$	0.008	(0.639)
β_{E_O}	0.987	(0.055)	$\beta_{E_O E_E}$	0.09	(0.467)
β_{E_G}	-0.130	(0.632)	$\beta_{E_G E_G}$	0.153	(0.000)
β_{E_E}	-0.001	(0.999)	$\beta_{E_G E_E}$	-0.130	(0.000)
$\beta_{E_C E_C}$	0.153	(0.000)	$\beta_{E_E E_E}$	0.195	(0.001)
$\beta_{E_C E_O}$	-0.027	(0.027)	α_{E_C}	-0.077	(0.803)
$\beta_{E_C E_G}$	-0.031	(0.001)	α_{E_O}	-1.471	(0.094)
$\beta_{E_C E_E}$	-0.094	(0.000)	α_{E_G}	0.604	(0.195)
$\beta_{E_O E_O}$	-0.010	(0.752)	α_{E_E}	0.944	(0.382)
Log likelihood		235.4441	LR statistic ($\forall \alpha_{E_i} = 0$)		20.6575

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-30. Parameter Estimates (US)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.193	(0.000)	$\beta_{E_O E_G}$	-0.046	(0.000)
β_{E_O}	-1.434	(0.000)	$\beta_{E_O E_E}$	-0.115	(0.000)
β_{E_G}	0.224	(0.054)	$\beta_{E_G E_G}$	0.250	(0.000)
β_{E_E}	2.017	(0.000)	$\beta_{E_G E_E}$	-0.204	(0.000)
$\beta_{E_C E_C}$	0.092	(0.000)	$\beta_{E_E E_E}$	0.393	(0.000)
$\beta_{E_C E_O}$	-0.018	(0.000)	α_{E_C}	-0.329	(0.003)
$\beta_{E_C E_G}$	0.000	(0.991)	α_{E_O}	3.249	(0.000)
$\beta_{E_C E_E}$	-0.074	(0.000)	α_{E_G}	0.039	(0.870)
$\beta_{E_O E_O}$	0.180	(0.000)	α_{E_E}	-2.959	(0.000)
Log likelihood		261.9176	LR statistic ($\forall \alpha_{E_i} = 0$)		43.934

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

1. 4. Other Assets (K_4)

Table A-II-31. Parameter Estimates (Italy)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.033	(0.000)	$\beta_{E_O E_G}$	-0.045	(0.002)
β_{E_O}	0.575	(0.000)	$\beta_{E_O E_E}$	-0.248	(0.000)
β_{E_G}	0.006	(0.396)	$\beta_{E_G E_G}$	0.048	(0.016)
β_{E_E}	0.386	(0.000)	$\beta_{E_G E_E}$	-0.001	(0.938)
$\beta_{E_C E_C}$	0.011	(0.000)	$\beta_{E_E E_E}$	0.252	(0.000)
$\beta_{E_C E_O}$	-0.007	(0.067)	α_{E_C}	-3.024	(0.000)
$\beta_{E_C E_G}$	-0.002	(0.709)	α_{E_O}	-74.493	(0.000)
$\beta_{E_C E_E}$	-0.003	(0.131)	α_{E_G}	17.533	(0.000)
$\beta_{E_O E_O}$	0.300	(0.000)	α_{E_E}	59.984	(0.000)
Log likelihood		311.3142	LR statistic ($\forall \alpha_{E_i} = 0$)		108.650

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-32. Parameter Estimates (Japan)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.046	(0.000)	$\beta_{E_O E_G}$	0.001	(0.589)
β_{E_O}	0.286	(0.000)	$\beta_{E_O E_E}$	-0.138	(0.000)
β_{E_G}	-0.002	(0.691)	$\beta_{E_G E_G}$	0.031	(0.000)
β_{E_E}	0.670	(0.000)	$\beta_{E_G E_E}$	-0.036	(0.000)
$\beta_{E_C E_C}$	0.050	(0.000)	$\beta_{E_E E_E}$	0.228	(0.000)
$\beta_{E_C E_O}$	-0.001	(0.768)	α_{E_C}	0.004	(0.953)
$\beta_{E_C E_G}$	0.004	(0.239)	α_{E_O}	-1.114	(0.000)
$\beta_{E_C E_E}$	-0.054	(0.000)	α_{E_G}	0.296	(0.000)
$\beta_{E_O E_O}$	0.138	(0.000)	α_{E_E}	0.814	(0.000)
Log likelihood		327.0135	LR statistic ($\forall \alpha_{E_i} = 0$)		64.844

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-33. Parameter Estimates (Netherlands)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	-0.002	(0.879)	$\beta_{E_O E_G}$	0.089	(0.002)
β_{E_O}	0.561	(0.000)	$\beta_{E_O E_E}$	-0.168	(0.002)
β_{E_G}	0.392	(0.000)	$\beta_{E_G E_G}$	0.056	(0.117)
β_{E_E}	0.050	(0.518)	$\beta_{E_G E_E}$	-0.126	(0.008)
$\beta_{E_C E_C}$	0.049	(0.000)	$\beta_{E_E E_E}$	0.312	(0.000)
$\beta_{E_C E_O}$	-0.011	(0.142)	α_{E_C}	0.585	(0.037)
$\beta_{E_C E_G}$	-0.019	(0.003)	α_{E_O}	-9.536	(0.000)
$\beta_{E_C E_E}$	-0.019	(0.083)	α_{E_G}	-1.750	(0.145)
$\beta_{E_O E_O}$	0.090	(0.047)	α_{E_E}	10.701	(0.000)
Log likelihood		245.2776	LR statistic ($\forall \alpha_{E_i} = 0$)		29.040

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-34. Parameter Estimates (US)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.049	(0.000)	$\beta_{E_O E_G}$	-0.057	(0.000)
β_{E_O}	0.225	(0.000)	$\beta_{E_O E_E}$	-0.112	(0.000)
β_{E_G}	0.244	(0.000)	$\beta_{E_G E_G}$	0.259	(0.000)
β_{E_E}	0.481	(0.000)	$\beta_{E_G E_E}$	-0.211	(0.000)
$\beta_{E_C E_C}$	0.033	(0.037)	$\beta_{E_E E_E}$	0.352	(0.000)
$\beta_{E_C E_O}$	-0.015	(0.000)	α_{E_C}	-2.716	(0.008)
$\beta_{E_C E_G}$	0.010	(0.000)	α_{E_O}	-14.631	(0.000)
$\beta_{E_C E_E}$	-0.028	(0.044)	α_{E_G}	-0.472	(0.616)
$\beta_{E_O E_O}$	0.184	(0.000)	α_{E_E}	17.819	(0.000)
Log likelihood		274.2120	LR statistic ($\forall \alpha_{E_i} = 0$)		68.522

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

1. 5. Non-Residential Structure (K_5)

Table A-II-35. Parameter Estimates (Australia)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	-0.106	(0.000)	$\beta_{E_O E_G}$	0.007	(0.754)
β_{E_O}	-0.974	(0.000)	$\beta_{E_O E_E}$	-0.083	(0.387)
β_{E_G}	0.412	(0.000)	$\beta_{E_G E_G}$	0.125	(0.000)
β_{E_E}	1.668	(0.000)	$\beta_{E_G E_E}$	-0.103	(0.000)
$\beta_{E_C E_C}$	0.033	(0.000)	$\beta_{E_E E_E}$	0.221	(0.009)
$\beta_{E_C E_O}$	0.030	(0.005)	α_{E_C}	0.396	(0.000)
$\beta_{E_C E_G}$	-0.029	(0.000)	α_{E_O}	2.904	(0.000)
$\beta_{E_C E_E}$	-0.035	(0.000)	α_{E_G}	-0.554	(0.000)
$\beta_{E_O E_O}$	0.046	(0.660)	α_{E_E}	-2.745	(0.000)
Log likelihood		279.3314	LR statistic ($\forall \alpha_{E_i} = 0$)		58.470

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-36. Parameter Estimates (Austria)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	-0.404	(0.000)	$\beta_{E_O E_G}$	0.003	(0.900)
β_{E_O}	-0.737	(0.000)	$\beta_{E_O E_E}$	0.081	(0.000)
β_{E_G}	0.615	(0.001)	$\beta_{E_G E_G}$	0.081	(0.101)
β_{E_E}	1.527	(0.000)	$\beta_{E_G E_E}$	-0.113	(0.003)
$\beta_{E_C E_C}$	0.027	(0.646)	$\beta_{E_E E_E}$	0.043	(0.232)
$\beta_{E_C E_O}$	-0.044	(0.000)	α_{E_C}	0.971	(0.000)
$\beta_{E_C E_G}$	0.029	(0.418)	α_{E_O}	1.743	(0.000)
$\beta_{E_C E_E}$	-0.011	(0.749)	α_{E_G}	-0.955	(0.015)
$\beta_{E_O E_O}$	-0.040	(0.020)	α_{E_E}	-1.759	(0.000)
Log likelihood		253.0880	LR statistic ($\forall \alpha_{E_i} = 0$)		44.247

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-37. Parameter Estimates (Denmark)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	-0.044	(0.168)	$\beta_{E_O E_G}$	-0.224	(0.000)
β_{E_O}	-1.444	(0.000)	$\beta_{E_O E_E}$	-0.077	(0.000)
β_{E_G}	1.842	(0.000)	$\beta_{E_G E_G}$	0.402	(0.000)
β_{E_E}	0.645	(0.000)	$\beta_{E_G E_E}$	-0.180	(0.000)
$\beta_{E_C E_C}$	0.056	(0.000)	$\beta_{E_E E_E}$	0.287	(0.000)
$\beta_{E_C E_O}$	-0.026	(0.000)	α_{E_C}	0.193	(0.005)
$\beta_{E_C E_G}$	0.002	(0.728)	α_{E_O}	3.675	(0.000)
$\beta_{E_C E_E}$	-0.031	(0.000)	α_{E_G}	-3.483	(0.000)
$\beta_{E_O E_O}$	0.327	(0.000)	α_{E_E}	-0.386	(0.260)
Log likelihood		215.4829	LR statistic ($\forall \alpha_{E_i} = 0$)		48.375

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-38. Parameter Estimates (Finland)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.079	(0.111)	$\beta_{E_O E_G}$	-0.041	(0.000)
β_{E_O}	-1.193	(0.000)	$\beta_{E_O E_E}$	-0.180	(0.002)
β_{E_G}	0.359	(0.000)	$\beta_{E_G E_G}$	0.079	(0.000)
β_{E_E}	1.755	(0.000)	$\beta_{E_G E_E}$	-0.027	(0.007)
$\beta_{E_C E_C}$	0.175	(0.000)	$\beta_{E_E E_E}$	0.278	(0.000)
$\beta_{E_C E_O}$	-0.093	(0.000)	α_{E_C}	0.084	(0.433)
$\beta_{E_C E_G}$	-0.011	(0.034)	α_{E_O}	3.155	(0.000)
$\beta_{E_C E_E}$	-0.071	(0.003)	α_{E_G}	-0.563	(0.000)
$\beta_{E_O E_O}$	0.314	(0.000)	α_{E_E}	-2.677	(0.000)
Log likelihood		254.8960	LR statistic ($\forall \alpha_{E_i} = 0$)		27.200

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-39. Parameter Estimates (Italy)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	-0.067	(0.001)	$\beta_{E_O E_G}$	-0.001	(0.954)
β_{E_O}	-2.658	(0.000)	$\beta_{E_O E_E}$	0.032	(0.487)
β_{E_G}	0.700	(0.000)	$\beta_{E_G E_G}$	0.087	(0.000)
β_{E_E}	3.025	(0.000)	$\beta_{E_G E_E}$	-0.073	(0.000)
$\beta_{E_C E_C}$	0.013	(0.000)	$\beta_{E_E E_E}$	0.030	(0.515)
$\beta_{E_C E_O}$	-0.011	(0.046)	α_{E_C}	0.192	(0.000)
$\beta_{E_C E_G}$	-0.013	(0.075)	α_{E_O}	6.469	(0.000)
$\beta_{E_C E_E}$	0.011	(0.002)	α_{E_G}	-1.371	(0.000)
$\beta_{E_O E_O}$	-0.00	(0.662)	α_{E_E}	-5.289	(0.000)
Log likelihood		287.4899	LR statistic ($\forall \alpha_{E_i} = 0$)		61.001

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-40. Parameter Estimates (Japan)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.042	(0.000)	$\beta_{E_O E_G}$	-0.001	(0.521)
β_{E_O}	-0.042	(0.094)	$\beta_{E_O E_E}$	-0.145	(0.000)
β_{E_G}	0.088	(0.000)	$\beta_{E_G E_G}$	0.023	(0.000)
β_{E_E}	0.912	(0.000)	$\beta_{E_G E_E}$	-0.027	(0.000)
$\beta_{E_C E_C}$	0.053	(0.000)	$\beta_{E_E E_E}$	0.228	(0.000)
$\beta_{E_C E_O}$	-0.001	(0.839)	α_{E_C}	0.011	(0.595)
$\beta_{E_C E_G}$	0.005	(0.173)	α_{E_O}	0.414	(0.000)
$\beta_{E_C E_E}$	-0.057	(0.000)	α_{E_G}	-0.117	(0.000)
$\beta_{E_O E_O}$	0.146	(0.000)	α_{E_E}	-0.308	(0.000)
Log likelihood		327.7440	LR statistic ($\forall \alpha_{E_i} = 0$)		66.305

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-41. Parameter Estimates (Korea)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	-0.028	(0.006)	$\beta_{E_O E_G}$	0.065	(0.000)
β_{E_O}	-0.221	(0.211)	$\beta_{E_O E_E}$	0.149	(0.000)
β_{E_G}	0.124	(0.009)	$\beta_{E_G E_G}$	0.017	(0.291)
β_{E_E}	1.125	(0.000)	$\beta_{E_G E_E}$	-0.089	(0.000)
$\beta_{E_C E_C}$	0.012	(0.000)	$\beta_{E_E E_E}$	-0.055	(0.000)
$\beta_{E_C E_O}$	-0.014	(0.000)	α_{E_C}	0.154	(0.000)
$\beta_{E_C E_G}$	0.007	(0.004)	α_{E_O}	1.982	(0.001)
$\beta_{E_C E_E}$	-0.005	(0.009)	α_{E_G}	-0.424	(0.007)
$\beta_{E_O E_O}$	-0.200	(0.000)	α_{E_E}	-1.712	(0.000)
Log likelihood		262.7887	LR statistic ($\forall \alpha_{E_i} = 0$)		16.797

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-42. Parameter Estimates (Netherlands)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.041	(0.099)	$\beta_{E_O E_G}$	0.084	(0.000)
β_{E_O}	-0.261	(0.000)	$\beta_{E_O E_E}$	-0.015	(0.305)
β_{E_G}	0.058	(0.110)	$\beta_{E_G E_G}$	0.136	(0.000)
β_{E_E}	1.162	(0.000)	$\beta_{E_G E_E}$	-0.203	(0.000)
$\beta_{E_C E_C}$	0.052	(0.000)	$\beta_{E_E E_E}$	0.250	(0.000)
$\beta_{E_C E_O}$	-0.002	(0.724)	α_{E_C}	-0.033	(0.544)
$\beta_{E_C E_G}$	-0.017	(0.077)	α_{E_O}	0.832	(0.000)
$\beta_{E_C E_E}$	-0.032	(0.000)	α_{E_G}	0.583	(0.000)
$\beta_{E_O E_O}$	-0.066	(0.034)	α_{E_E}	-1.382	(0.000)
Log likelihood		271.9657	LR statistic ($\forall \alpha_{E_i} = 0$)		82.417

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-43. Parameter Estimates (UK)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.038	(0.597)	$\beta_{E_O E_G}$	0.003	(0.697)
β_{E_O}	-0.821	(0.000)	$\beta_{E_O E_E}$	-0.026	(0.009)
β_{E_G}	-0.085	(0.364)	$\beta_{E_G E_G}$	0.108	(0.000)
β_{E_E}	1.868	(0.000)	$\beta_{E_G E_E}$	-0.093	(0.000)
$\beta_{E_C E_C}$	0.137	(0.000)	$\beta_{E_E E_E}$	0.198	(0.000)
$\beta_{E_C E_O}$	-0.039	(0.000)	α_{E_C}	0.185	(0.390)
$\beta_{E_C E_G}$	-0.019	(0.012)	α_{E_O}	2.844	(0.000)
$\beta_{E_C E_E}$	-0.079	(0.000)	α_{E_G}	0.914	(0.001)
$\beta_{E_O E_O}$	0.062	(0.000)	α_{E_E}	-3.942	(0.000)
Log likelihood		257.2816	LR statistic ($\forall \alpha_{E_i} = 0$)		64.333

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-44. Parameter Estimates (US)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	-0.048	(0.128)	$\beta_{E_O E_G}$	-0.057	(0.000)
β_{E_O}	-0.426	(0.000)	$\beta_{E_O E_E}$	-0.141	(0.000)
β_{E_G}	0.219	(0.000)	$\beta_{E_G E_G}$	0.259	(0.000)
β_{E_E}	1.256	(0.000)	$\beta_{E_G E_E}$	-0.210	(0.000)
$\beta_{E_C E_C}$	0.043	(0.000)	$\beta_{E_E E_E}$	0.390	(0.000)
$\beta_{E_C E_O}$	-0.012	(0.004)	α_{E_C}	0.199	(0.012)
$\beta_{E_C E_G}$	0.008	(0.004)	α_{E_O}	1.371	(0.000)
$\beta_{E_C E_E}$	-0.039	(0.000)	α_{E_G}	0.055	(0.561)
$\beta_{E_O E_O}$	0.210	(0.000)	α_{E_E}	-1.625	(0.000)
Log likelihood		265.4468	LR statistic ($\forall \alpha_{E_i} = 0$)		50.992

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

1. 6. Residential Structure (K_6)

Table A-II-45. Parameter Estimates (Korea)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.023	(0.000)	$\beta_{E_O E_G}$	0.020	(0.017)
β_{E_O}	0.344	(0.000)	$\beta_{E_O E_E}$	0.069	(0.000)
β_{E_G}	0.008	(0.065)	$\beta_{E_G E_G}$	0.046	(0.000)
β_{E_E}	0.625	(0.000)	$\beta_{E_G E_E}$	-0.070	(0.000)
$\beta_{E_C E_C}$	-0.006	(0.002)	$\beta_{E_E E_E}$	-0.006	(0.690)
$\beta_{E_C E_O}$	-0.007	(0.008)	α_{E_C}	-0.148	(0.000)
$\beta_{E_C E_G}$	0.005	(0.046)	α_{E_O}	0.386	(0.447)
$\beta_{E_C E_E}$	0.008	(0.000)	α_{E_G}	-0.151	(0.036)
$\beta_{E_O E_O}$	-0.082	(0.000)	α_{E_E}	-0.088	(0.850)
Log likelihood		263.3611	LR statistic ($\forall \alpha_{E_i} = 0$)		17.942

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-46. Parameter Estimates (Netherlands)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.159	(0.000)	$\beta_{E_O E_G}$	0.004	(0.905)
β_{E_O}	-0.167	(0.749)	$\beta_{E_O E_E}$	0.131	(0.034)
β_{E_G}	-0.105	(0.542)	$\beta_{E_G E_G}$	0.038	(0.231)
β_{E_E}	1.113	(0.053)	$\beta_{E_G E_E}$	-0.031	(0.336)
$\beta_{E_C E_C}$	0.048	(0.000)	$\beta_{E_E E_E}$	-0.060	(0.376)
$\beta_{E_C E_O}$	0.004	(0.424)	α_{E_C}	-74.382	(0.002)
$\beta_{E_C E_G}$	-0.011	(0.011)	α_{E_O}	144.340	(0.621)
$\beta_{E_C E_E}$	-0.040	(0.000)	α_{E_G}	227.578	(0.018)
$\beta_{E_O E_O}$	-0.139	(0.007)	α_{E_E}	-297.5352	(0.356)
Log likelihood		238.1365	LR statistic ($\forall \alpha_{E_i} = 0$)		14.758

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

2. Comparison of the Extended Energy Sub-Model with the Original Energy Sub-Model

2. 1. The Original Energy Sub-Model

Table A-II-47. Parameter Estimates (Australia)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.054	(0.000)	$\beta_{E_CE_E}$	-0.046	(0.130)
β_{E_O}	0.195	(0.000)	$\beta_{E_OE_O}$	0.389	(0.124)
β_{E_G}	0.189	(0.000)	$\beta_{E_OE_G}$	-0.064	(0.186)
β_{E_E}	0.562	(0.000)	$\beta_{E_OE_E}$	-0.394	(0.101)
$\beta_{E_CE_C}$	0.025	(0.000)	$\beta_{E_GE_G}$	0.144	(0.000)
$\beta_{E_CE_O}$	0.068	(0.047)	$\beta_{E_GE_E}$	-0.033	(0.521)
$\beta_{E_CE_G}$	-0.047	(0.000)	$\beta_{E_EE_E}$	0.473	(0.032)
Log likelihood		250.0965	Observation		28

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-48. Parameter Estimates (Austria)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.035	(0.000)	$\beta_{E_CE_E}$	-0.131	(0.000)
β_{E_O}	0.055	(0.000)	$\beta_{E_OE_O}$	0.080	(0.072)
β_{E_G}	0.191	(0.000)	$\beta_{E_OE_G}$	0.027	(0.419)
β_{E_E}	0.719	(0.000)	$\beta_{E_OE_E}$	-0.099	(0.051)
$\beta_{E_CE_C}$	0.058	(0.112)	$\beta_{E_GE_G}$	-0.118	(0.148)
$\beta_{E_CE_O}$	-0.008	(0.702)	$\beta_{E_GE_E}$	0.010	(0.816)
$\beta_{E_CE_G}$	0.081	(0.038)	$\beta_{E_EE_E}$	0.220	(0.000)
Log likelihood		230.9645	Observation		28

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-49. Parameter Estimates (Denmark)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.046	(0.000)	$\beta_{E_CE_E}$	-0.054	(0.000)
β_{E_O}	0.182	(0.000)	$\beta_{E_OE_O}$	0.415	(0.001)
β_{E_G}	0.297	(0.000)	$\beta_{E_OE_G}$	-0.314	(0.001)
β_{E_E}	0.475	(0.000)	$\beta_{E_OE_E}$	-0.077	(0.000)
$\beta_{E_CE_C}$	0.053	(0.000)	$\beta_{E_GE_G}$	0.447	(0.000)
$\beta_{E_CE_O}$	-0.025	(0.002)	$\beta_{E_GE_E}$	-0.160	(0.000)
$\beta_{E_CE_G}$	0.026	(0.000)	$\beta_{E_EE_E}$	0.291	(0.000)
Log likelihood		191.2952	Observation		24

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-50. Parameter Estimates (Finland)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.118	(0.000)	$\beta_{E_CE_E}$	-0.075	(0.002)
β_{E_O}	0.301	(0.000)	$\beta_{E_OE_O}$	-0.085	(0.360)
β_{E_G}	0.093	(0.000)	$\beta_{E_OE_G}$	0.028	(0.074)
β_{E_E}	0.488	(0.000)	$\beta_{E_OE_E}$	0.160	(0.027)
$\beta_{E_CE_C}$	0.186	(0.000)	$\beta_{E_GE_G}$	0.065	(0.000)
$\beta_{E_CE_O}$	-0.102	(0.000)	$\beta_{E_GE_E}$	-0.085	(0.000)
$\beta_{E_CE_G}$	-0.008	(0.035)	$\beta_{E_EE_E}$	0.000	(0.997)
Log likelihood		241.2960	Observation		28

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-51. Parameter Estimates (Italy)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.018	(0.000)	$\beta_{E_CE_E}$	0.008	(0.042)
β_{E_O}	0.207	(0.000)	$\beta_{E_OE_O}$	0.100	(0.222)
β_{E_G}	0.093	(0.000)	$\beta_{E_OE_G}$	-0.019	(0.341)
β_{E_E}	0.682	(0.000)	$\beta_{E_OE_E}$	-0.073	(0.287)
$\beta_{E_CE_C}$	0.014	(0.000)	$\beta_{E_GE_G}$	0.081	(0.000)
$\beta_{E_CE_O}$	-0.007	(0.256)	$\beta_{E_GE_E}$	-0.047	(0.004)
$\beta_{E_CE_G}$	-0.014	(0.112)	$\beta_{E_EE_E}$	0.112	(0.066)
Log likelihood		256.9892	Observation		28

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-52. Parameter Estimates (Japan)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.047	(0.000)	$\beta_{E_CE_E}$	-0.054	(0.000)
β_{E_O}	0.157	(0.000)	$\beta_{E_OE_O}$	0.132	(0.000)
β_{E_G}	0.033	(0.000)	$\beta_{E_OE_G}$	0.002	(0.703)
β_{E_E}	0.763	(0.000)	$\beta_{E_OE_E}$	-0.132	(0.000)
$\beta_{E_CE_C}$	0.047	(0.000)	$\beta_{E_GE_G}$	0.038	(0.000)
$\beta_{E_CE_O}$	-0.001	(0.619)	$\beta_{E_GE_E}$	-0.047	(0.000)
$\beta_{E_CE_G}$	0.008	(0.000)	$\beta_{E_EE_E}$	0.233	(0.000)
Log likelihood		294.5915	Observation		27

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-53. Parameter Estimates (Korea)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.019	(0.000)	$\beta_{E_CE_E}$	-0.015	(0.000)
β_{E_O}	0.367	(0.000)	$\beta_{E_OE_O}$	-0.127	(0.000)
β_{E_G}	-0.002	(0.344)	$\beta_{E_OE_G}$	0.055	(0.000)
β_{E_E}	0.616	(0.000)	$\beta_{E_OE_E}$	0.081	(0.000)
$\beta_{E_CE_C}$	0.020	(0.000)	$\beta_{E_GE_G}$	0.014	(0.365)
$\beta_{E_CE_O}$	-0.009	(0.001)	$\beta_{E_GE_E}$	-0.073	(0.000)
$\beta_{E_CE_G}$	0.004	(0.150)	$\beta_{E_EE_E}$	0.008	(0.471)
Log likelihood		254.3901	Observation		23

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-54. Parameter Estimates (Netherlands)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.027	(0.000)	$\beta_{E_CE_E}$	-0.043	(0.000)
β_{E_O}	0.089	(0.000)	$\beta_{E_OE_O}$	-0.138	(0.004)
β_{E_G}	0.300	(0.000)	$\beta_{E_OE_G}$	0.008	(0.801)
β_{E_E}	0.583	(0.000)	$\beta_{E_OE_E}$	0.128	(0.032)
$\beta_{E_CE_C}$	0.053	(0.000)	$\beta_{E_GE_G}$	0.041	(0.198)
$\beta_{E_CE_O}$	0.002	(0.786)	$\beta_{E_GE_E}$	-0.037	(0.271)
$\beta_{E_CE_G}$	-0.013	(0.025)	$\beta_{E_EE_E}$	-0.048	(0.483)
Log likelihood		230.7574	Observation		28

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-55. Parameter Estimates (UK)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.100	(0.000)	$\beta_{E_CE_E}$	-0.078	(0.000)
β_{E_O}	0.129	(0.000)	$\beta_{E_OE_O}$	0.056	(0.001)
β_{E_G}	0.218	(0.000)	$\beta_{E_OE_G}$	0.029	(0.001)
β_{E_E}	0.554	(0.000)	$\beta_{E_OE_E}$	-0.035	(0.078)
$\beta_{E_CE_C}$	0.130	(0.000)	$\beta_{E_GE_G}$	0.099	(0.000)
$\beta_{E_CE_O}$	-0.050	(0.000)	$\beta_{E_GE_E}$	-0.127	(0.000)
$\beta_{E_CE_G}$	-0.002	(0.842)	$\beta_{E_EE_E}$	0.240	(0.000)
Log likelihood		225.1153	Observation		28

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-56. Parameter Estimates (US)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.034	(0.000)	$\beta_{E_CE_E}$	-0.060	(0.000)
β_{E_O}	0.128	(0.000)	$\beta_{E_OE_O}$	0.224	(0.000)
β_{E_G}	0.241	(0.000)	$\beta_{E_OE_G}$	-0.058	(0.000)
β_{E_E}	0.597	(0.000)	$\beta_{E_OE_E}$	-0.147	(0.000)
$\beta_{E_CE_C}$	0.075	(0.000)	$\beta_{E_GE_G}$	0.261	(0.000)
$\beta_{E_CE_O}$	-0.019	(0.000)	$\beta_{E_GE_E}$	-0.206	(0.000)
$\beta_{E_CE_G}$	0.004	(0.327)	$\beta_{E_EE_E}$	0.413	(0.000)
Log likelihood		239.9508	Observation		28

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

2. 2. The Extended Energy Sub-Model (Final Version)

Table A-II-57. Parameter Estimates (Australia)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.283	(0.000)	$\beta_{E_O E_G}$	0.013	(0.468)
β_{E_O}	1.889	(0.000)	$\beta_{E_O E_E}$	-0.060	(0.471)
β_{E_G}	-0.140	(0.041)	$\beta_{E_G E_G}$	0.119	(0.000)
β_{E_E}	-1.033	(0.000)	$\beta_{E_G E_E}$	-0.108	(0.000)
$\beta_{E_C E_C}$	0.031	(0.000)	$\beta_{E_E E_E}$	0.202	(0.005)
$\beta_{E_C E_O}$	0.027	(0.002)	α_{E_C}	-0.437	(0.000)
$\beta_{E_C E_G}$	-0.025	(0.000)	α_{E_O}	-3.224	(0.000)
$\beta_{E_C E_E}$	-0.034	(0.000)	α_{E_G}	0.625	(0.000)
$\beta_{E_O E_O}$	0.019	(0.836)	α_{E_E}	3.037	(0.000)
Log likelihood		285.0775	LR statistic ($\forall \alpha_{E_i} = 0$)		69.962

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-58. Parameter Estimates (Austria)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.419	(0.016)	$\beta_{E_O E_G}$	-0.020	(0.607)
β_{E_O}	0.915	(0.000)	$\beta_{E_O E_E}$	0.087	(0.000)
β_{E_G}	-0.066	(0.788)	$\beta_{E_G E_G}$	0.071	(0.346)
β_{E_E}	-0.268	(0.231)	$\beta_{E_G E_E}$	-0.064	(0.223)
$\beta_{E_C E_C}$	0.052	(0.535)	$\beta_{E_E E_E}$	0.010	(0.869)
$\beta_{E_C E_O}$	-0.031	(0.122)	α_{E_C}	-0.736	(0.031)
$\beta_{E_C E_G}$	0.012	(0.814)	α_{E_O}	-1.659	(0.000)
$\beta_{E_C E_E}$	-0.033	(0.595)	α_{E_G}	0.477	(0.312)
$\beta_{E_O E_O}$	-0.036	(0.199)	α_{E_E}	1.918	(0.000)
Log likelihood		242.119	LR statistic ($\forall \alpha_{E_i} = 0$)		22.309

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-59. Parameter Estimates (Denmark)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.122	(0.014)	$\beta_{E_O E_G}$	-0.137	(0.073)
β_{E_O}	3.029	(0.000)	$\beta_{E_O E_E}$	-0.080	(0.000)
β_{E_G}	-2.725	(0.000)	$\beta_{E_G E_G}$	0.324	(5.233)
β_{E_E}	0.574	(0.000)	$\beta_{E_G E_E}$	-0.200	(0.000)
$\beta_{E_C E_C}$	0.061	(0.000)	$\beta_{E_E E_E}$	0.323	(0.000)
$\beta_{E_C E_O}$	-0.031	(0.000)	α_{E_C}	-0.151	(0.116)
$\beta_{E_C E_G}$	0.012	(0.052)	α_{E_O}	-5.478	(0.000)
$\beta_{E_C E_E}$	-0.042	(0.000)	α_{E_G}	5.832	(0.000)
$\beta_{E_O E_O}$	0.248	(0.011)	α_{E_E}	-0.203	(0.461)
Log likelihood		213.955	LR statistic ($\forall \alpha_{E_i} = 0$)		45.319

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-60. Parameter Estimates (Finland)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.173	(0.001)	$\beta_{E_O E_G}$	-0.052	(0.000)
β_{E_O}	1.780	(0.000)	$\beta_{E_O E_E}$	-0.226	(0.000)
β_{E_G}	-0.181	(0.000)	$\beta_{E_G E_G}$	0.083	(0.000)
β_{E_E}	-0.773	(0.000)	$\beta_{E_G E_E}$	-0.019	(0.044)
$\beta_{E_C E_C}$	0.169	(0.000)	$\beta_{E_E E_E}$	0.341	(0.000)
$\beta_{E_C E_O}$	-0.087	(0.000)	α_{E_C}	-0.108	(0.275)
$\beta_{E_C E_G}$	-0.013	(0.018)	α_{E_O}	-2.981	(0.000)
$\beta_{E_C E_E}$	-0.069	(0.003)	α_{E_G}	0.550	(0.000)
$\beta_{E_O E_O}$	0.364	(0.000)	α_{E_E}	2.539	(0.000)
Log likelihood		260.35	LR statistic ($\forall \alpha_{E_i} = 0$)		38.101

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-61. Parameter Estimates (Italy)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.117	(0.000)	$\beta_{E_O E_G}$	-0.008	(0.437)
β_{E_O}	3.364	(0.000)	$\beta_{E_O E_E}$	0.002	(0.951)
β_{E_G}	-0.584	(0.000)	$\beta_{E_G E_G}$	0.088	(0.000)
β_{E_E}	-1.897	(0.000)	$\beta_{E_G E_E}$	-0.068	(0.000)
$\beta_{E_C E_C}$	0.012	(0.000)	$\beta_{E_E E_E}$	0.055	(0.200)
$\beta_{E_C E_O}$	-0.011	(0.047)	α_{E_C}	-0.185	(0.000)
$\beta_{E_C E_G}$	-0.012	(0.077)	α_{E_O}	-5.950	(0.000)
$\beta_{E_C E_E}$	0.011	(0.002)	α_{E_G}	1.274	(0.000)
$\beta_{E_O E_O}$	0.017	(0.694)	α_{E_E}	4.861	(0.000)
Log likelihood		296.233	LR statistic ($\forall \alpha_{E_i} = 0$)		78.487

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-62. Parameter Estimates (Japan)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.051	(0.000)	$\beta_{E_O E_G}$	0.001	(0.732)
β_{E_O}	0.364	(0.000)	$\beta_{E_O E_E}$	-0.140	(0.000)
β_{E_G}	-0.023	(0.002)	$\beta_{E_G E_G}$	0.024	(0.000)
β_{E_E}	0.608	(0.000)	$\beta_{E_G E_E}$	-0.031	(0.000)
$\beta_{E_C E_C}$	0.052	(0.000)	$\beta_{E_E E_E}$	0.227	(0.000)
$\beta_{E_C E_O}$	-0.001	(0.781)	α_{E_C}	-0.008	(0.672)
$\beta_{E_C E_G}$	0.006	(0.088)	α_{E_O}	-0.414	(0.000)
$\beta_{E_C E_E}$	-0.057	(0.000)	α_{E_G}	0.111	(0.000)
$\beta_{E_O E_O}$	0.140	(0.000)	α_{E_E}	0.312	(0.000)
Log likelihood		325.593	LR statistic ($\forall \alpha_{E_i} = 0$)		62.003

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-63. Parameter Estimates (Korea)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	-0.003	(0.843)	$\beta_{E_O E_G}$	0.033	(0.002)
β_{E_O}	1.081	(0.000)	$\beta_{E_O E_E}$	0.057	(0.000)
β_{E_G}	-0.205	(0.000)	$\beta_{E_G E_G}$	0.034	(0.008)
β_{E_E}	0.128	(0.503)	$\beta_{E_G E_E}$	-0.064	(0.000)
$\beta_{E_C E_C}$	0.008	(0.004)	$\beta_{E_E E_E}$	0.014	(0.217)
$\beta_{E_C E_O}$	0.000	(0.889)	α_{E_C}	0.036	(0.189)
$\beta_{E_C E_G}$	-0.002	(0.319)	α_{E_O}	-1.257	(0.000)
$\beta_{E_C E_E}$	-0.006	(0.011)	α_{E_G}	0.360	(0.000)
$\beta_{E_O E_O}$	-0.090	(0.000)	α_{E_E}	0.871	(0.010)
Log likelihood		262.046	LR statistic ($\forall \alpha_{E_i} = 0$)		15.311

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-64. Parameter Estimates (Netherlands)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.006	(0.838)	$\beta_{E_O E_G}$	0.090	(0.000)
β_{E_O}	0.567	(0.000)	$\beta_{E_O E_E}$	-0.031	(0.028)
β_{E_G}	0.612	(0.000)	$\beta_{E_G E_G}$	0.131	(0.000)
β_{E_E}	-0.185	(0.000)	$\beta_{E_G E_E}$	-0.203	(0.000)
$\beta_{E_C E_C}$	0.053	(0.000)	$\beta_{E_E E_E}$	0.266	(0.000)
$\beta_{E_C E_O}$	-0.003	(0.652)	α_{E_C}	0.038	(0.463)
$\beta_{E_C E_G}$	-0.018	(0.068)	α_{E_O}	-0.856	(0.000)
$\beta_{E_C E_E}$	-0.032	(0.000)	α_{E_G}	-0.553	(0.000)
$\beta_{E_O E_O}$	-0.056	(0.062)	α_{E_E}	1.370	(0.000)
Log likelihood		269.711	LR statistic ($\forall \alpha_{E_i} = 0$)		77.906

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-65. Parameter Estimates (UK)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.228	(0.017)	$\beta_{E_O E_G}$	0.027	(0.001)
β_{E_O}	0.931	(0.000)	$\beta_{E_O E_E}$	-0.085	(0.000)
β_{E_G}	0.450	(0.000)	$\beta_{E_G E_G}$	0.100	(0.000)
β_{E_E}	-0.611	(0.000)	$\beta_{E_G E_E}$	-0.117	(0.000)
$\beta_{E_C E_C}$	0.112	(0.000)	$\beta_{E_E E_E}$	0.251	(0.000)
$\beta_{E_C E_O}$	-0.052	(0.000)	α_{E_C}	-0.210	(0.174)
$\beta_{E_C E_G}$	-0.010	(0.131)	α_{E_O}	-1.1311	(0.000)
$\beta_{E_C E_E}$	-0.050	(0.000)	α_{E_G}	-0.375	(0.000)
$\beta_{E_O E_O}$	0.110	(0.000)	α_{E_E}	1.896	(0.000)
Log likelihood		271.708	LR statistic ($\forall \alpha_{E_i} = 0$)		93.185

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

Table A-II-66. Parameter Estimates (US)

Parameter	Estimates	p-value	Parameter	Estimate	p-value
β_{E_C}	0.152	(0.003)	$\beta_{E_O E_G}$	-0.057	(0.000)
β_{E_O}	0.926	(0.000)	$\beta_{E_O E_E}$	-0.131	(0.000)
β_{E_G}	0.274	(0.000)	$\beta_{E_G E_G}$	0.259	(0.000)
β_{E_E}	-0.352	(0.000)	$\beta_{E_G E_E}$	-0.211	(0.000)
$\beta_{E_C E_C}$	0.041	(0.003)	$\beta_{E_E E_E}$	1.719	(0.000)
$\beta_{E_C E_O}$	-0.013	(0.001)	α_{E_C}	-0.217	(0.018)
$\beta_{E_C E_G}$	0.008	(0.002)	α_{E_O}	-1.443	(0.000)
$\beta_{E_C E_E}$	-0.037	(0.02)	α_{E_G}	-0.060	(0.543)
$\beta_{E_O E_O}$	0.201	(0.000)	α_{E_E}	1.719	(0.000)
Log likelihood		267.138	LR statistic ($\forall \alpha_{E_i} = 0$)		54.375

[a] E_C: Coal, E_O: Oil, E_G: Gas, E_E: Electricity

APPENDIX III

Table A-III-.1 Elasticity of Substitution (Australia)

	K		E		O	
K	-0.163	(-3.953)	0.165	(4.308)	0.254	(3.461)
E	0.097	(2.156)	-0.205	(-3.415)	0.322	(2.743)
O	0.193	(3.896)	0.226	(3.327)	-0.051	(-3.381)

[a] K: Capital, E: Energy, O: Aggregate of labor and material

Table A-III-2. Elasticity of Substitution (Austria)

	K		E		(L+M)	
K	-0.327	(-10.584)	0.037	(2.598)	0.367	(8.206)
E	0.344	(8.755)	-0.031	(-3.145)	0.060	(1.784)
(L+M)	0.371	(10.312)	0.033	(3.042)	-0.046	(-6.943)

[a] K: Capital, E: Energy, O: Aggregate of labor and material

Table A-III-3. Elasticity of Substitution (Denmark)

	K		E		(L+M)	
K	-0.350	(-12.803)	0.246	(8.758)	0.349	(9.963)
E	0.374	(9.389)	-0.129	(-7.214)	0.151	(3.795)
(L+M)	0.386	(12.680)	0.139	(6.767)	-0.046	(-7.698)

[a] K: Capital, E: Energy, O: Aggregate of labor and material

Table A-III-4. Elasticity of Substitution (Finland)

	K		E		(L+M)	
K	-0.287	(-6.145)	0.228	(5.003)	0.449	(9.023)
E	0.157	(2.357)	-0.298	(-8.760)	0.521	(13.397)
(L+M)	0.341	(6.456)	0.336	(9.299)	-0.093	(-12.898)

[a] K: Capital, E: Energy, O: Aggregate of labor and material

Table A-III-5. Elasticity of Substitution (Italy)

	K		E		(L+M)	
K	-0.416	(-13.654)	0.045	(2.867)	0.541	(15.132)
E	0.330	(8.316)	-0.098	(-5.991)	0.256	(8.439)
(L+M)	0.469	(13.926)	0.117	(6.199)	-0.072	(-14.255)

[a] K: Capital, E: Energy, O: Aggregate of labor and material

Table A-III-6. Elasticity of Substitution (Japan)

	K		E		(L+M)	
K	-0.841	(-20.324)	0.661	(0.348)	0.983	(23.433)
E	0.985	(11.348)	-0.633	(-18.176)	0.659	(8.958)
(L+M)	0.993	(20.729)	0.651	(17.658)	-0.169	(-25.159)

[a] K: Capital, E: Energy, O: Aggregate of labor and material

Table A-III-7. Elasticity of Substitution (Korea)

	K		E		(L+M)	
K	-0.582	(-13.932)	0.299	(7.440)	0.677	(14.855)
E	0.588	(10.408)	-0.289	(-7.333)	0.388	(6.509)
(L+M)	0.649	(14.198)	0.327	(7.119)	-0.105	(-12.566)

[a] K: Capital, E: Energy, O: Aggregate of labor and material

Table A-III-8. Elasticity of Substitution (Netherlands)

	K		E		(L+M)	
K	-0.156	(-1.742)	-0.290	(-5.829)	0.311	(2.670)
E	-0.011	(0.016)	0.172	(2.843)	0.032	(1.400)
(L+M)	0.188	(1.848)	-0.167	(-2.501)	-0.037	(-2.600)

[a] K: Capital, E: Energy, O: Aggregate of labor and material

Table A-III-9. Elasticity of Substitution (UK)

	K		E		(L+M)	
K	-0.166	(-9.302)	-0.041	(1.148)	0.201	(5.142)
E	0.145	(7.615)	0.031	(-1.497)	0.015	(1.476)
(L+M)	0.186	(8.701)	-0.026	(1.433)	-0.026	(-3.573)

[a] K: Capital, E: Energy, O: Aggregate of labor and material

Table A-III-10. Elasticity of Substitution (US)

	K		E		(L+M)	
K	-0.374	(-8.077)	0.219	(4.233)	0.330	(5.283)
E	0.533	(13.224)	-0.130	(-3.382)	0.015	(1.264)
(L+M)	0.416	(7.703)	0.133	(3.221)	-0.045	(-4.887)

[a] K: Capital, E: Energy, O: Aggregate of labor and material

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Separability and Substitutability between Energy and Capital: Evidences from KLEM Analyses of 10 OECD Countries

에너지와 자본재 간 분리성과 대체성 연구: OECD 10개국 KLEM 생산구조 분석

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요약 (국문 초록)

KLEM 모형은 계량경제학적 기법을 이용해 산업용 에너지 수요를 분석하는 대표적인 모형 중 하나이다. KLEM 모형을 확립한 Berndt and Wood (1975)의 연구 이래, 이 모형은 에너지 경제학 분야에서 전세계적으로 널리 사용되어 왔다. KLEM 모형을 이용하여, 에너지원 간 대체성(interfuel substitutability)와 생산요소 간 대체성(interfactor substitutability)을 분석할 수 있다. 본 논문은 에너지 경제학에서 이슈가 되

어온 에너지-자본 간 대체가능성을 KLEM 모형을 적용하여 연구하였다.

에너지-자본 간 대체가능성 분석 시 2개의 쟁점이 있다. 첫 번째는 KLEM 모형의 응용연구 시 일반적으로 가정되어 온 분리성(separability)의 문제이다. 분리성은 여러 생산요소의 통합을 가능하게 하는 기초가 되는 개념이다. 분리성에 근거하여 수십 종류의 생산요소를 자본(K), 노동(L), 에너지(E), 원재료(M)의 네 요소로 통합할 수 있다. 이 가정은 산업에서의 에너지-자본 간 대체성을 정확히 분석하는 데 제약이 된다. 분리성은 상이한 자본재 간의 대체가 에너지원 간의 대체와 무관하다고 가정한다. 그러나 실제 산업에서는 어떠한 종류의 자본 설비에 투자하느냐가 어떤 에너지원을 사용할지 결정하는 경향이 있다. 이러한 맥락에서, 분리성의 가정은 특정 자본재 선택에 따른 에너지 믹스 변화를 간과하게 한다.

두 번째 쟁점은 과연 에너지와 자본 간에 대체성 존재 여부이다. Griffin and Gregory (1976)이 '에너지-자본 가설 (energy-capital hypothesis)'를 제시한 이래, 많은 연구자들은 에너지와 자본이 서로 대체재인지 보완재인지 지속적으로 논의해왔다. 이를 논의한 이유는 만약 에너지와 자본이 대체재 관계에 있다면 에너지 가격 인상 혹은 자본 투자를 통해 에너지 사용량을 감소시킬 수 있기 때문이다. 많은 논의에도 불구하고

에너지-자본 간 대체성에 관해서 아직까지 일치되는 견해가 도출되지는 않았다. 한편, 에너지-자본 간 대체성이 에너지 효율적인 기술의 채택을 의미하려면, 자본에 의한 에너지 대체가 에너지에 대한 자본 대체보다 커야 한다. 그러나 기존의 많은 문헌들은 대체성 그 자체에 집중한 나머지, 대체성 방향의 문제를 간과하였다. 일부 논문(Thompson and Taylor, 1995; Welsch and Ochsen, 2005; Feng and Serletis, 2008)에서만 에너지-자본 간 대체성이 비대칭적 특성을 가짐을 보였다. 즉, 에너지-자본간 대체성의 방향에 대한 논의가 절대적으로 부족한 상황이다.

이에 본 논문에서는 상기에 2개 이슈에 초점을 맞추어 에너지-자본 간 분리성과 대체성을 연구하였다. 1980년 이후 OECD 10개 가입국의 제조업 자료를 분석하여 에너지-자본 간 분리성과 대체성에 관하여 일반화 시킬 수 있는 결과를 도출하려고 시도하였다. 이를 통하여 산업용 에너지 수요 정책 수립에 적용할 수 있는 시사점을 도출하였다. 관련하여 다음의 3개 주제를 연구하였다.

첫째, 에너지-자본 간 분리성을 가정하는 것이 이론적으로 적합한지 분석하였다. 에너지와 자본의 하위 요소를 분류한 뒤, 이들 간의 분리성 상황(separability case) 및 이에 결부되는 분리성 유형(separability pattern)을 도출하였다. 총 3개의 분리성 상황 및 16개의 분리성 유형 분석 결과, 분석한 모든

국가에 대하여 에너지-자본 간 분리성을 가정하는 것이 적합하지 않음을 확인하였다. 이는 KLEM 모형의 응용연구 시, 에너지와 자본을 각각 하위요소로 나누어 분석하는 것이 바람직함을 의미한다.

둘째, KLEM 모형의 하위모형인 Energy Sub-model(Fuss, 1977)을 적용하여, 자본재 종류에 따라 개별 에너지원의 수요에 미치는 영향이 어떻게 달라지는지 분석하였다. ICT assets, transport equipment, other machinery, other assets, non-residential structures, residential structures의 6개 자본재 투입이 에너지원 간 관계에 미치는 영향을 각각 분석한 결과, ICT assets, other machinery, other assets은 전기 사용량을 증가시키는 반면, 나머지 자본재들은 그 특성이 명확히 나타나지 않았다. 따라서, ICT assets, other machinery, other assets을 전기 사용을 증가시키는 자본재(EK)로 정의하고, 나머지 자본재들을 NK로 정의하였다. EK와 NK의 투입을 고려한 extended energy sub-model과 그렇지 않은 energy sub-model의 분석결과를 비교하였다. 그 결과, extended energy sub-model이 energy sub-model에 비해 설명력과 정확성이 높은 결과를 제시하는 경향이 있는 것으로 나타났다. 에너지원 간 대체성을 분석한 결과 에너지 independence가 높은 나라일수록 에너지원 간 대체가 활발하지 않은 것으로 나타났다.

셋째, 에너지 수요에 미치는 영향을 고려하여 에너지와

자본을 분리하였을 때, 에너지와 자본 간 대체성은 어떠한 특징을 가지는지 분석하였다. KLEM 모형을 분석하였으며, 생산요소로는 EK, NK, 전기, 연료, 그 외 생산요소 (노동과 재료의 합)을 가정하였다. 분석결과, 에너지에 의한 자본 대체가 자본에 의한 에너지 대체보다 우세한 것으로 나타났다. 특히, 자본재는 연료를 대체하기 보다는 보완하는 경향이 대부분의 국가에서 우세하게 나타났다. 이러한 에너지-자본 간 비대칭적 대체성은 산업에서 자본재 투자의 의사결정이 에너지 수요 결정에 선행한다는 Hartman (1979)의 설명에 부합한다. 이는 에너지 가격 정책이 에너지 효율 설비 채택을 유도하지 못한다는 기존의 연구결과(de Groot et al., 2001; Kim, 2010; OTA, 1993; Velthuijsen, 1993)을 뒷받침한다.

이상의 연구결과에 따른 본 논문의 의의는 크게 다섯 가지로 나누어 볼 수 있다. 먼저 본 논문은 에너지-자본 간 분리성의 이슈를 이론적, 실증적으로 심도 있게 고찰한 최초의 논문으로써, 관련된 학술연구에 기여할 수 있을 것이다. 둘째, 본 연구는 자본재 분류에 있어 새로운 시각을 제시하였다. 전기수요에 미치는 영향을 고려했을 때 제조업에서 투입되는 자본재는 크게 2개 유형으로 나누어질 수 있음을 보였다. 셋째, 본 논문은 10개 주요국의 에너지-자본재 간 일반적인 대체성의 특성을 밝혔다. 에너지-자본재 간 대체성/보완성 문제는 1970년대 이후 에너지 경제학계의 주요 화두였는데, 이에

관한 가능한 해답을 제시하였다는 데 큰 의의가 있다. 넷째, 본 논문은 에너지-자본 간 비대칭적 대체성을 분석하여, 산업용 에너지 수요 정책에 활용할 수 있는 시사점을 도출하였다. 에너지는 자본을 대체하지만 자본이 에너지를 반드시 대체하는 것은 아니므로, 에너지 가격 정책이 산업용 에너지 수요의 조절에 큰 효과를 발휘하기 어려움을 역설하였다. 넷째, 본 논문은 OECD 가입국 10개 국가의 생산요소 간 대체성 및 에너지원 간 대체성을 비교하였다. 이는 국가 간 성장을 비교하는 논의에 활용될 수 있다.

주요어: KLEM 모형, 분리성, 생산요소 간 대체성, 에너지원 간 대체성, 에너지-자본 대체성

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