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Inter-Industry Linkages, Energy and CO_2 Multipliers of the Electric Power Industry in Thailand

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ABSTRACT

The vital electricity generation sector contributes substantially to CO_2 emission in Thailand. In this study 19 relevant sectors, based on input-output tables for the years of 2000, 2005 and 2010, have been aggregated to investigate inter-industry linkages among the power sector and other sectors. Also, the energy multiplier and CO_2 multiplier are applied to estimate the direct and indirect energy intensity and CO_2 intensity of 19 industries during 2010. Results show that the electricity generation sector has a high forward linkage effect and a relatively low backward linkage effect. Consequently, the electricity generation sector has a significant influence as an input source for other industries, but it has a low capacity for attracting other industries' output. In 2010 the electricity generation sector was the highest energy intensive and CO_2 intensive industry with 1,770 × 10^7 kcal million US$$^{-1}$ and 3,521 ton CO_2 million US$$^{-1}$, respectively. Besides, total indirect energy intensity and total indirect CO_2 intensity from the aggregated 19 sectors accounted for 53% and 52% of the total intensity, respectively. Accordingly, the huge indirect energy intensity and CO_2 intensity in the construction, machinery, other manufacturing played significant role in Thai's industry, and should not be overlooked. To promote energy conservation and emissions reduction by the electricity generation and other relevant sectors, this study suggests that the Thai government should promote sustainable design of buildings and improve the electricity transmission and distribution processes. Besides, the environmental impact assessment should be undertaken for proposed nuclear power plant construction in the future. The methodology used herein can be applied to other industries, and they can also provide a guide for governments to evaluate relative economic contribution and environmental impact on energy consumption and CO_2 emission.

Keywords: Input-output analysis; Multiplier effect; Energy consumption; CO_2 emission; Electricity generation sector.

INTRODUCTION

Energy is required for economic development of a country. Electricity is one of the convenient, efficient, and versatile forms of commercial energy. The electricity generation sector in Thailand is a fundamental sector that influences and supports other industries; thus, it is considered as a principal part of the industrial growth and economic development of the country. The trends of gross domestic product (GDP) at constant 2010 prices in billion US dollars (USD) and final energy consumption during 2000–2014 are shown in Fig. 1. Thailand's final energy consumption grew from 48.6 million tonne of oil equivalent (Mtoe) in 2000 to 75.8 Mtoe in 2014, with an average growth rate of 3.26% per year (Department of Alternative Energy Development and Efficiency, 2005, 2010b, 2014a). The country's GDP for the same period rose from 158.7 billion USD to 335.7 billion USD for a constant 2010 price, accounting for 5.74% average growth per year (World Bank Group, 2015). Due to the Asian financial crisis in 2008, the economic development in Thailand decreased in 2009 (Fig. 1).

The manufacturing industry sector plays an important role in Thailand's economy. In 2014, energy consumption in the industrial sector accounted for 37.2% of the total energy consumption, followed by the transportation, residential, commercial, and agricultural sectors with shares of 35.3%, 15.1%, 7.2%, and 5.2%, respectively (Department of Alternative Energy Development and Efficiency, 2014b). The industrial and commercial sectors are the dominant sectors that depended heavily on electricity consumption during 2000–2014. Total electric consumption of the economic sectors in 2014 was 168.7 Twh, of which 69.7 Twh were consumed by the industrial sector, 58.2 Twh by the commercial sector, and 0.1 Twh by the transportation sector (Department of Alternative Energy Development and Efficiency, 2014a). Moreover, 48% of total CO_2 emission

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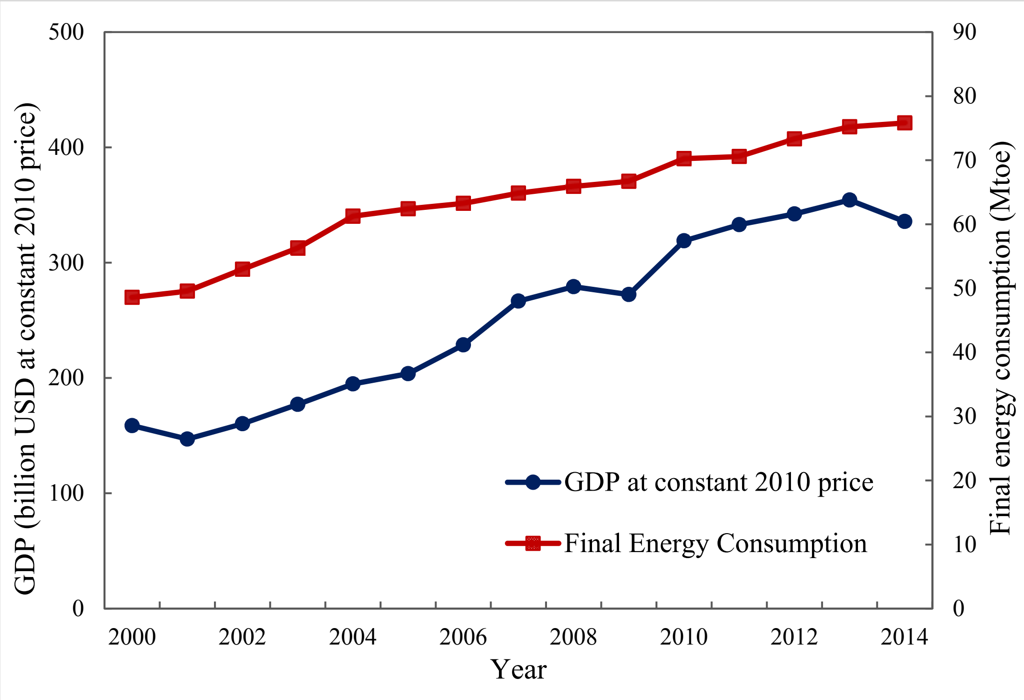

Fig. 1. Thailand's Gross Domestic Product (GDP) and final energy consumption for 2000–2014.

in 2014 came from the electricity generation sector, while transportation, manufacturing, others and residential and commercial sectors emitted 23%, 19%, 6% and 4%, respectively, to the total CO_2 emission (Department of Alternative Energy Development and Efficiency, 2014a). That is, Thailand's electricity generation sector is the largest source of CO_2 emission.

Climate change and global warming issues have been the recent focus of worldwide attention. According to the United Nation Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP21) in Paris in December 2015, the expected key result was an agreement to keep global warming below 2°C compared to pre-industrial levels (Climate Stewards, 2015). Moreover, countries across the globe committed to create a new international climate agreement known as their Intended Nationally Determined Contributions (INDCs) which would put them on a path toward a low-carbon and climate-resilient future. Thailand's INDC aimed to reduce its greenhouse gas (GHG) emission by 20 percent from the projected business-as-usual (BAU) level by 2030 (United Nations Framework Convention on Climate Change, 2015). Thailand's INDC actions are in line with national development plans; such as the Thailand Power Development Plan 2015 (PDP 2015) and the 20-Year Energy Efficiency Development Plan (EEDP). For example, the PDP 2015 set a target to achieve a 20% share of power generation from renewable sources in 2036, while the EEDP aims to reduce the country's energy intensity by 25% in 2030 (Ministry of Energy, 2011, 2015). In addition, the Climate Change Master Plan B.E. 2015–2050 was formulated in order to achieve climate-resilient and low-carbon growth in the line with sustainable development by 2050 (United Nations Framework Convention on Climate Change, 2015).

GHGs are mostly generated from the energy conversion of fossil fuels, which are also the driving force behind the economic growth. Hence, a reduction in energy use would reduce GHG emissions accompanied by a slowdown in economic growth due to increased prices assuming no changes in production technology and efficiency (Yu and Choi, 1985; Tonn, 2003). As a result, the issue is how to account for economic growth, energy consumption and CO_2 emissions. For example, Liu *et al.* (2013) constructed an integrated performance evaluation model by data envelopment analysis (DEA) to examine seven thermal power plants operating in Taiwan during 2001–2008. Results indicated that the integrated efficiency and production scale of some plants were inefficient, with reductions in fuel consumption and CO_2 emissions identified as the major strategies to improve efficiency. Liou *et al.* (2015) modified conventional two-stage DEA to analyze the energy use efficiency and the economic efficiency of 28 Organization for Economic Co-operation and Development (OECD) countries during 2005 to 2007. Findings showed that OECD countries are only interested in economic development, have little regard for energy use efficiency, and continue to discharge too much CO_2. Lin *et al.* (2015) evaluated the decoupling of CO_2 emissions from GDP in South Africa using OECD and Tapio for the period of 1990 to 2012, and they investigated the primary CO_2 emission drivers with the Kaya identity. Results showed that a strong decoupling occurred during 2010–2012, and the increase in population, GDP per capita, and adverse energy efficiency were the primary driving forces for increased CO_2 emission. Li *et al.* (2016) reviewed challenges and perspectives on carbon fixation and utilization technologies. Results revealed that CO_2 fixation via fast-growing biomass reduces CO_2 uses for furnishing chemicals and energy products, while integrated alkaline waste treatment with CO_2 capture and utilization is an attractive approach to achieving direct and indirect reduction of GHG emissions from industries.

Global warming is not only associated with fossil fuel combustion, but it also relates to emission from the linkages among industrial sectors. To cope with the embodied CO_2 emission and energy consumption from various industries, the application of Input-Output Analysis (IOA) allows one to trace the direct and indirect energy and environmental impacts of changes in the final demand throughout an economy (Machado *et al.*, 2001; Smith *et al.*, 2006). Standard models of Input-Output (IO) were first proposed by Leontief. Leontief (1936) assumed that all inputs were bought by producers in fixed proportions, the production function being of the complementary inputs type; it is characterized as demand-driven model. On the other hand, Ghosh (1958) proposed another IO model which assumed that, each commodity in IO framework is sold to each sector in fixed proportions; it is characterized as supply-driven model. The Ghosh inverse is calculated from the allocation coefficient which measured as a fraction of total output in order to examine allocation processes of input industry sectors (Ghosh, 1958). Furthermore, the application of the Ghosh model is suitable for forward linkage measures, but it not backward linkage ones. That is, row sums of the Ghosh inverse, namely $(I-B)^{-1}$, were suggested to measure total forward linkages (Miller and Blair, 2009). However, the forward linkage based on the row sum of the Leontief inverse matrix was suggested as better measure of the direct forward linkage (Rasmussen, 1956). De Mesnard (2009) demonstrated that it is impossible to simultaneously choose the Leontief model for the backward effects and the Ghosh model for the forward effects because each model is based on a different assumption. The technical coefficients in the Leontief model are inter-industry coefficients that produce total inputs corresponding to demand requirement (Park, 2007). Also, the technical coefficient enables one to review information relating to the purchased units of input one industry that are required produce one unit of output in another industry. This helps one to understand the relationship between industries. Overall, the Leontief model has been recognized and widely used in IOA research for decades, such as in national accounting or in regional economics. Hence, the Leontief model was adopted in our study.

IOA has been applied extensively in the field of energy-related CO_2 emissions, embodied pollution trade, environmental economics, and policy scenario studies. Kofoworola and Gheewala (2008) examined the relationship of Thailand’s construction to other economic sectors by using three IO tables for 1995, 1998 and 2000. Their results explained that the backward effect of the Thai construction sector is much larger than the forward effect. Bekhet and Yasmin (2014) applied IOA to examine the impact of the 2008–2009 Global Financial Crisis (GFC) on economic growth and energy consumption in Malaysia. They found that the decline in exports caused by the GFC led to a decrease in GDP of 13%. Cui *et al.* (2015) focused on the energy embodied in China's foreign trade with a multi-regional IO approach for 2001–2007. Their results indicated that the energy embodied was increasing rapidly and that China was an energy exporter, rather than an energy importer, in terms of embodied energy. Moreover, a number of studies have connected IOA to several methodologies so as to focus on integrating life cycle assessment (LCA), structural decomposition analysis (SDA), and multiplier analysis. IOA is an important part of LCA because IOA provides a feasible means to complement the system boundary of conventional LCA approaches (Xin *et al.*, 2015). In addition, the concept of the multiplier was first derived by Wright (1974) for defining the energy commodity in the IOA. He presented energy costs per unit of money value and the energy costs of different commodities. Lin *et al.* (2012) focused on the IO table for 42 sectors in Taiwan in 2004 and 2006 for assessing the impacts that link each sector to CO_2 emissions and the CO_2 multipliers. Results revealed that the electricity sector was significant influences other industrial development in Taiwan.

IOA is an effective approach not only for estimating the embodied emissions for a regional economy, but also for connecting with other methods for an extended research. This research, the electric power industry is one of the energy consumptive source, and the dominant source of CO_2 emissions in Thailand. Also, this sector is a major contributor to the evolution of the Thai economy. Consequently, this study focuses on the economic-based linkage effects of energy consumption and CO_2 emission of the electricity generation in Thailand. The aim is to investigate the inter-industry relationship of the electricity generation sectors for the 19 sector input-output table for the years 2000, 2005, and 2010, to estimate forward and backward linkage effects of the 19 aggregated sectors by using the sensibility index of dispersion and the power index of dispersion, and to quantify the energy intensity, CO_2 intensity of the aggregated 19 sectors through the energy multiplier and CO_2 multiplier, as well as the proportion of total direct and indirect of both energy consumption and CO_2 emissions for the base year of 2010. From our results, suggestions related to policy implementation can be of value to the relevant agencies in Thailand.

The next section describes the IOA, linkage effect calculation, and multiplier analysis methodologies. The third section provides the details of the database employed in this study. Section four presents the results and discussion. The final section gives a conclusion of our findings with comments about policy implementation.

METHODS

Input-Output Analysis

The input-output model was first introduced by Leontief who received the Nobel Prize in 1973 for the development of the IO method and its application to important economic problems (Lin *et al.*, 2012). The IO model basically describes the interconnection of the industries, households, and government entities in which the output of an industry will appear as the input of other industries. These can help to track the flow of money from one entity to the next.

Hence, IOA can not only show the description and details of activities throughout an economy, but it can also compute the direct and indirect environmental flows triggered by a given final demand (Leontief, 1970; Miller and Blair, 1985). Furthermore, Leontief (1970) explained that the balances between the total input and the aggregate output of each product and service in a given economic system can be defined by linear equations. The basic equations of the IO can be expressed as following (Lin and Chang, 1997):

$$\sum_{j=1}^{n} x_{ij} + F_i = X_i \tag{1}$$

$$\sum_{i=1}^{n} x_{ij} + V_j = X_j \tag{2}$$

$$\sum_{j=1}^{n} a_{ij} X_j + F_i = X_i \tag{3}$$

where X_i = total gross output produced in sector i,
X_j = total gross input required in sector j,
F_i = the product of sector i delivered to the final demand
V_j = final payment (value added) by sector j
x_{ij} = the amount of the product sector i used by per unit of output of sector j
$a_{ij} = x_{ij}/X_j$ the direct input or technical coefficients from product sector i used by per unit of output sector j.

In other words, the technical coefficient presents each unit of the output value for the sector j that required a certain amount of money to buy directly from sector i. Therefore, the technical structure of the entire system can be represented by the matrix of technical IO coefficients of all its sectors. Eq. (3) can be rewritten in the following matrix in order to get the Leontief inverse matrix (Lin and Chang, 1997; Lin *et al.*, 2012):

$$AX + F = X$$
$$(I - A)X = F$$
or
$$X[I - A]^{-1}F \tag{4}$$

where A = the direct input coefficient matrix of a_{ij},
I = the identity matrix,
$[I - A]^{-1}$ = the Leontief inverse matrix, representing the total direct and indirect requirement of sector i by per unit of output sector j to final demand,

Linkage Effect Analysis

The idea of linkage effect was introduced by Hirschman (1958). Based on his assumption, the economy in related industries can be boosted through linking the input and output activities. The production by particular sectors in the IO model has two effects on the other sectors in the economy; these effects are known as forward and backward linkages. Backward linkage is the consumptive relationship formed during the use of intermediate goods bought from the upstream industries by the downstream industries, while forward linkage is the supply relationship formed when the upstream industry supplies the produced intermediate goods to the downstream industry (Lenzen, 2003; Ali, 2015). In other words, the backward linkage measures the impact on the supplier industries of a unit increase in the final demand for a product. The forward linkage represents the increase in sector i needed to supply the input required to produce a unit of the final demand output in sector j (Miller and Lahr, 2001). However, backward and forward linkages have extensively been used for determining appropriate development strategies through the identification of sectors creating above average impacts upon an economy (Hirschman, 1958).

The power of dispersion index has been widely applied as a measure of backward linkage effect. On the other hand, the sensitivity of dispersion index has been interpreted as a measure of forward linkage effect (Kofoworola and Gheewala, 2008). Both indices are defined as the following (Lin and Chang, 1997):

$$U_i^f = \frac{\sum_{j=1}^{n} b_{ij}}{\frac{1}{n}\sum_{i=1}^{n} b_{ij} \sum_{j=1}^{n} b_{ij}} \tag{5}$$

$$U_j^b = \frac{\sum_{i=1}^{n} b_{ij}}{\frac{1}{n}\sum_{i=1}^{n} b_{ij} \sum_{j=1}^{n} b_{ij}} \tag{6}$$

where U_i^f = the sensibility index of dispersion, denoting the forward linkage effect,
U_j^b = the power index of dispersion, denoting the backward linkage effect,
b_{ij} = the element of the Leontief inverse matrix,
$\sum_{j=1}^{n} b_{ij}$ = the sum of elements in row i of the Leontief inverse matrix,
$\sum_{i=1}^{n} b_{ij}$ = the sum of elements in column j of the Leontief inverse matrix.

Industries with both power of dispersion and sensitivity of dispersion values greater than one play significant roles in economic development in supporting other industries as well as boosting other industries (Yoo and Yoo, 2009).

Multiplier Analysis

The multiplier effect reveals an economy of an exogenous stimulus via an increase in one or more components of final demand (Miller and Lahr, 2001). Multiplier analysis may also be used to measure the total change throughout the economy arising from one unit change in a given industry or sector. Following the logic behind the IO representation of pollution processes, an exogenous increase in the final demand of activities will lead to an increase in sector production to cover the new demand (Butnar and Llop, 2007). Various types of emission can be related in a measurable way to energy consumption or production processes, where pollution is considered to be the "externality" of the general economic activities (Miller and Blair, 2009). In this study, the externality can also be connected to the IO model in order to respond to the environmental effects of Thailand's electricity generation sector by other industrial processes. The energy multiplier was estimated by the following equation (Lin and Chang, 1997):

$$R = r(I - A)^{-1} \quad (7)$$

$$Q = q(I - A)^{-1} \quad (8)$$

where $R = [r_j]_{1\times n}$, Energy Multiplier, total impact of energy coefficient, which specifies the amount of energy consumption required directly and indirectly caused by per $\$10^6$ worth of output of industry j, 10^7 kcal million US$$^{-1}$,

$Q = [q_j]_{1\times n}$, CO_2 Multiplier, the total impact of CO_2 emissions, which specifies the amount of CO_2 emitted directly and indirectly caused by per $\$10^6$ worth of output of industry j, ton CO_2 million US$$^{-1}$,

$(I - A)^{-1}$ = the Leontief inverse matrix,

$r = [r_j]_{1\times n}$, energy consumption coefficient from industry j (10^7 kcal million US$$^{-1}$),

$q = [q_j]_{1\times n}$, CO_2 emission coefficient from industry j (ton CO_2 million US$$^{-1}$).

DATA ACQUISITION

Thailand has produced benchmark national IO tables since 1975; they are compiled and released every five years.

Its first IO was compiled by the Office of the National Economic and Social Development Board (NESDB) in cooperation with Chulalongkorn University, the National Statistical Office (NSO), and the Institute of Developing Economies (IDE), Japan (Kwangmoon *et al.*, 2011). However, NESDB complies and has published Thailand's IO tables from IO table in 1980, and the IO table in 2010 is the latest one available for our study. We adopted three economic IO tables that include a 180-sector table for 2000, 2005 and 2010 (National Economic and Social Development Board, 2000, 2005, 2010) for this study.

The statistical energy consumption data of Thailand for years 2000, 2005, and 2010 are obtained from the Thailand Energy Balance Sheets by the International Energy Agency (IEA) (International Energy Agency, 2003, 2008, 2012) which shows a flow from supply transformation to final consumption by the major industrial sectors. Since the sector classifications of the IO table from NESDB and those of the Thailand Energy Balance Sheets from IEA are not consistent, we aggregated all the IO transaction tables and energy balance tables into 19 sectors to simplify the calculation and interpretation of results, as described in Table 1. Furthermore, the gross output of 19 sectors in the multiplier calculation is based on year 2010. GDP in Fig. 1 was obtained from the World Bank Data (World Bank Group, 2015). CO_2 emissions from fuel consumption in 19 sectors was calculated according to the revised 2006 IPPC (IPCC, 2006). The estimated of SO_2 and NO_x emissions were obtained from the reports of Thailand energy situation (Department of Alternative Energy Development and Efficiency, 2005, 2010b).

Table 1. Sector Classification.

	Sector	Energy Balance Sheets (IEA) [a]	180-sector I-O table (NESDB)[b]
1.	Agriculture and Forestry	53–54	1–29
2.	Petroleum and Natural Gas Extraction	21	30–31
3.	Mining and Quarrying	35	32–41
4.	Food and Tobacco	36	42–60, 61–66
5.	Textile and Leather	40	67–74, 75–77
6.	Paper Products and Printing	37	81–83
7.	Wood and Wood Products	38	78–79
8.	Chemical Industries	30	84–92
9.	Petrochemical Industry	22	93–94
10.	Basic Metals	29, 31	105–107
11.	Non-metallic Products	32	99–104
12.	Electricity Generation and Gas Services	11–14, 47	135–136
13.	Machinery	33–34	108,110–128
14.	Construction	39	138–144
15.	Other Manufacturing	41	80, 95–98, 109, 129–134
16.	Road Transportation	45	150–151
17.	Other Transportation	43–44, 46, 48–49	149,153–154,156
18.	Wholesale Trade and Services	51–52	137, 145–148, 152, 155, 157–159, 160–178
19.	Unclassified	55	179–180

Source: [a] International Energy Agency (2003, 2008, 2012).
[b] National Economic and Social Development Board (2000, 2005, 2010).

RESULTS AND DISCUSSION

Inter-Industry Relationships

Forward and backward linkage effects of all sectors are shown in Table 3. Two important points were found in the results. The first point is the forward linkage effect of electricity generation and gas services sector was higher than those of other sectors, and was ranked in the top five sectors with the highest sensibility index of dispersion in 2000, 2005, and 2010. This means that the electricity generation and gas services sector is a vital input to other industries and services. The second point is that the electricity generation and gas services sector had a low value less than 1.0 for three years of backward linkage effect, and it was not ranked in the top five sector. The inputs of the electricity generation sector came from natural resources such as natural gas, coal, lignite, and oil. Most of the electricity inputs are not purchased from other industries, except those for the upstream sectors like petroleum and natural gas extraction. This implies that the power sector has less impact in consuming other industry's products.

Furthermore, the sectors with a high sensibility index of dispersion in 2000, 2005, and 2010, such as petroleum and natural gas extraction, mining and quarrying, basic metal, and agriculture and forestry sectors, also played important roles in supporting other industries in Thailand (Table 2). On the other hand, the machinery, wholesale trade and services, food and tobacco, and construction sectors had the largest backward linkage effects. The power index of dispersion of these sectors was larger than 1.0 for the three years; this indicates that these sectors have a greater impact in terms of investment expenditures in the national economy than the other sectors. In other words, these sectors are a major contributor to production, export, earnings, employment, and income of the country. Table 4 displays the inter-industry relationship of the electricity generation and gas services sector in Thailand. The sensibility index of dispersion decreased from 1.201 in 2000 to 1.182 in 2010, whereas the power index of dispersion of the electricity sector increased from 0.859 in 2000 to 0.875 in 2010.

The top ten sectors with high forward and backward linkages to the electricity sectors in 2010 are listed in Table 3. Results indicated that the top 10 forward linkage sectors were the major suppliers to the electricity generation sector, especially the petroleum and natural gas extraction and petrochemical industry sectors. As more electricity is produced, the demand of intermediate input from the upstream sectors like fuel mining and extraction sector are increased; therefore, these upstream sectors need to increase their outputs to meet the rising demand from electricity generation. On the contrary, the top 10 backward linkage sectors rely heavily on the electricity supply, particularly wholesale trade and services, machinery, and other manufacturing. The production processes of these industries are the main electricity consumers in Thailand.

Energy Multiplier

Energy consumption, the monetary energy consumption factors, and energy multipliers from the consumption of fossil fuels by the 19 industry sectors in 2010 are given in Table 5. Results show that the electricity generation and gas services, road transportation, and petrochemical industry sectors were the most dominant energy consumptive sources. Besides, for the monetary energy consumption factor, the electricity generation and gas services, road transportation, and petrochemical industry were the sectors with the highest direct energy consumption in 2010. This demonstrates that each of these sectors used lots of fuel to produce energy by itself rather than depending on external energy sources. If we calculate the energy consumption multiplier by multiplying the monetary energy consumption factors by the Leontief inverse matrix (Eq. (7)), results reveal that the electricity generation and gas services, road transportation, and wholesale trade and services were the major energy-intensive sectors among 19 sectors in Thailand. However, the energy multiplier for the wholesale trade and service sector was more than two times its monetary energy consumption factor. This shows that the level of indirect energy consumption from other related sectors was higher than the direct energy consumption from the wholesale trade and service itself. In fact, many sectors in Thailand have larger indirect energy consumption than direct energy consumption (Table 7). The discussion of direct and indirect energy consumption is presented in the next section.

CO_2 Multiplier

CO_2 emissions, the monetary CO_2 emission factors and CO_2 multipliers from fossil fuel combustion in 2010 are given in Table 6. CO_2 emissions from 19 sectors were computed from fuel consumption (natural gas, coal, petroleum product) multiplied by the emission coefficients from the revised 2006 IPPC (IPCC, 2006); the total CO_2 intensity (direct and indirect) was estimated according to Eq. (8). Results reveal that the major sources of CO_2 emissions were the electricity generation and gas service, petrochemical industry, and road transportation. The dominant sources of CO_2 emissions are the same as the major energy intensive ones because the sectors with high energy consumption release large amounts of CO_2. Regarding monetary CO_2 emission factor, the highest direct CO_2 intensive sectors in 2010 were electricity generation and gas service, road transportation, and non-metallic products. The non-metallic products emitted relatively high CO_2 emission, and its gross output product was small (Table 6); so, the non-metallic products sector was one of the significant sources of direct CO_2 emissions in 2010. The CO_2 multiplier is found by multiplying the monetary CO_2 emission factors with the Leontief inverse matrix (Eq. (8)). Results demonstrate that the dominant CO_2 intensive sectors were the electricity generation, and gas service, road transportation, and non-metallic products sectors.

Emissions from Major Economic Sectors

Based upon the Department of Alternative Energy Development and Efficiency (2005, 2010b) reports, the estimated carbon dioxide (CO_2), sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emissions from the major economic sectors, including transportation, power generation,

Table 2. Sectoral forward and backward linkage effects for 2000, 2005 and 2010.

Sector	Sensibility of dispersion						Power of dispersion					
	2000		2005		2010		2000		2005		2010	
	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank
1. Agriculture and Forestry	1.252	3	1.140	5	1.040	8	0.834	12	0.838	12	0.812	11
2. Petroleum and Natural Gas Extraction	1.664	1	1.466	2	1.542	2	0.565	18	0.578	18	0.548	18
3. Mining and Quarrying	1.386	2	1.786	1	1.855	1	0.540	19	0.542	19	0.503	19
4. Food and Tobacco	0.893	11	0.892	11	0.724	18	1.459	3	1.322	4	1.305	5
5. Textile and Leather	0.579	18	0.588	18	0.808	13	1.041	7	0.997	6	0.931	7
6. Paper Products and Printing	1.147	6	1.115	6	1.125	6	0.789	13	0.738	15	0.678	15
7. Wood and Wood Products	0.988	9	0.879	12	0.983	9	0.601	17	0.603	17	0.563	17
8. Chemical Industries	1.094	8	1.094	8	1.154	5	0.903	8	0.878	10	0.866	10
9. Petrochemical Industry	1.150	7	1.099	7	1.078	7	1.053	6	0.941	8	0.927	8
10. Basic Metals	1.226	4	1.256	3	1.302	3	0.752	14	0.874	11	0.728	13
11. Non-metallic Products	0.937	10	0.939	10	0.935	10	0.864	10	0.994	7	0.991	6
12. Electricity Generation and Gas Services	1.201	5	1.175	4	1.182	4	0.859	11	0.880	9	0.875	9
13. Machinery	0.884	12	0.854	13	0.784	16	1.869	1	2.042	1	2.400	1
14. Construction	0.536	19	0.547	19	0.522	19	1.438	4	1.466	3	1.451	3
15. Other Manufacturing	0.790	15	0.761	17	0.750	17	1.336	5	1.302	5	1.429	4
16. Road Transportation	0.765	17	0.812	15	0.808	12	0.888	9	0.758	13	0.730	12
17. Other Transportation	0.850	14	0.787	16	0.787	15	0.749	15	0.758	14	0.711	14
18. Whole Trade and Services	0.787	16	0.825	14	0.818	11	1.793	2	1.870	2	1.944	2
19. Unclassified	0.871	13	0.985	9	0.803	14	0.668	16	0.621	16	0.609	16

Table 3. Top 10 forward and backward linkage sectors relative to the electricity generation and gas services sector for 2000, 2005 and 2010.

Rank	Forward linkage effect			Backward linkage effect		
	2000	2005	2010	2000	2005	2010
1	Petroleum and Natural Gas Extraction	Petroleum and Natural Gas Extraction	Petroleum and Natural Gas Extraction	Wholesale Trade and services	Wholesale Trade and services	Wholesale Trade and services
2	Petrochemical Industry	Petrochemical Industry	Petrochemical Industry	Machinery	Machinery	Machinery
3	Wholesale Trade and services	Unclassified	Unclassified	Other Manufacturing	Food and Tobacco	Food and Tobacco
4	Road Transport	Wholesale Trade and services	Wholesale Trade and services	Chemical Industry	Other Manufacturing	Other Manufacturing
5	Paper Products and Printing	Road Transportation	Road Transportation	Food and Tobacco	Textile and Leather	Textile and Leather
6	Unclassified	Paper Products and Printing	Paper Products and Printing	Textile and Leather	Chemical Industry	Chemical Industry
7	Other Transportation	Machinery	Other Transportation	Non-metallic Products	Non-metallic Products	Non-metallic Products
8	Machinery	Mining and Quarrying	Chemical Industry	Construction	Basic Metals	Construction
9	Chemical Industry	Other Transportation	Machinery	Basic Metals	Construction	Agriculture and Forestry
10	Basic Metals	Chemical Industry	Basic Metals	Petrochemical Industry	Agriculture and Forestry	Basic Metals

Table 4. Inter-industry relationships of the electricity generation sector in Thailand for 2000, 2005, and 2010.

Year	Sensibility index of dispersion	Rank*	Power index of dispersion	Rank*	Overall linkage ranking	Rank*
2000	1.201	5	0.859	11	2.060	8
2005	1.175	4	0.880	9	2.055	7
2010	1.182	4	0.875	9	2.108	6

* Rank is the order of the electricity generation sector among the total 19 sectors.

Table 5. Energy consumption, monetary energy consumption factor and multiplier for 2010.

Sector	Gross Output (Million US$)	Energy Consumption (10^7 kcal)	Monetary Energy Consumption (10^7 kcal million US$$^{-1}$)	Energy Consumption Multiplier (10^7 kcal million US$$^{-1}$)
1. Agriculture and Forestry	60,041	3,499,866	58.29	198.78
2. Petroleum and Natural Gas Extraction	43,727	4,291,418	98.14	141.72
3. Mining and Quarrying	2,911	122,296	42.01	54.91
4. Food and Tobacco	83,349	7,711,316	92.52	439.23
5. Textile and Leather	32,987	782,659	23.73	205.94
6. Paper Products and Printing	12,014	1,411,231	117.47	185.23
7. Wood and Wood Products	3,477	230,116	66.18	89.93
8. Chemical Industries	49,704	2,221,850	44.70	234.58
9. Petrochemical industry	45,905	27,616,080	601.60	750.16
10.Basic Metals	38,913	1,501,421	38.58	104.30
11. Non-metallic Products	14,223	7,784,344	547.33	742.94
12. Electricity Generation and Gas Services	35,297	47,175,212	1,336.54	1,770.25
13. Machinery	245,573	1,501,637	6.07	762.95
14. Construction	28,875	167,472	5.80	529.85
15. Other Manufacturing	70,158	1,828,886	26.07	345.43
16. Road Transportation	22,600	19,298,560	853.97	1,024.04
17. Other Transportation	17,954	1,442,455	80.34	200.45
18. Wholesale Trade and Services	264,800	7,635,698	28.84	882.32
19. Unclassified	7,618	114,988	15.09	67.84

Table 6. CO_2 emission, monetary emission factor and multiplier for 2010.

Sector	Gross Output (Million US$)	CO_2 emissions (Ton CO_2)	Monetary CO_2 emission factor (Ton CO_2 million US$$^{-1}$)	CO_2 Multiplier (Ton CO_2 million US$$^{-1}$)
1. Agriculture and Forestry	60,041	10,958,117	182.51	577.07
2. Petroleum and Natural Gas Extraction	43,727	12,389,350	283.33	393.33
3. Mining and Quarrying	2,911	733,178	251.83	285.17
4. Food and Tobacco	83,349	34,025,760	408.23	1,367.94
5. Textile and Leather	32,987	4,658,327	141.22	610.29
6. Paper Products and Printing	12,014	4,906,960	408.45	612.39
7. Wood and Wood Products	3,477	1,235,854	355.42	436.19
8. Chemical Industries	49,704	10,443,299	210.11	714.09
9. Petrochemical Industry	45,905	66,226,679	1,442.71	1,839.81
10. Basic Metals	38,913	6,744,980	173.34	377.09
11. Non-metallic Products	14,223	31,721,471	2,230.38	2,905.62
12. Electricity Generation and Gas Service	35,297	91,796,052	2,600.71	3,521.69
13. Machinery	245,573	8,767,553	35.41	2,178.67
14. Construction	28,875	2,311,495	80.05	2,004.77
15. Other Manufacturing	70,158	6,755,200	96.29	1,051.44
16. Road Transportation	22,600	58,334,713	2,581.35	3,009.90
17. Other Transportation	17,954	4,664,694	259.81	566.32
18. Wholesale Trade and Services	264,800	37,556,380	141.83	2,280.01
19. Unclassified	7,618	564,867	74.15	239.49

Table 7. Direct/indirect effects of energy consumption for the 19 aggregated sectors in Thailand.

Sector	2010	
	Direct effect	Indirect effect
1. Agriculture and Forestry	29%	71%
2. Petroleum and Natural Gas Extraction	69%	31%
3. Mining and Quarrying	77%	23%
4. Food and Tobacco	21%	79%
5. Textile and Leather	12%	88%
6. Paper Products and Printing	63%	37%
7. Wood and Wood Products	74%	26%
8. Chemical Industries	19%	81%
9. Petrochemical Industry	80%	20%
10. Basic Metals	37%	63%
11. Non-metallic Products	74%	26%
12. Electricity Generation and Gas Services	76%	24%
13. Machinery	1%	99%
14. Construction	1%	99%
15. Other Manufacturing	8%	92%
16. Road Transportation	83%	17%
17. Other Transportation	40%	60%
18. Wholesale Trade and Services	3%	97%
19. Unclassified	22%	78%

manufacturing, residential and commercial, and others (agriculture, construction, mining) for 2000–2010 are shown in Figs. 2, 3 and 4. The electricity generation sector is the dominant source of CO_2, which accounts for 45% of the total CO_2 emissions in 2010, followed by the transportation (26%) and manufacturing (21%) sectors. In fact, natural gas shared 81.3% of total fuel consumption for power generation in Thailand in 2010, whereas the remaining share came from coal and lignite with 17.8%, and from oil with 0.9% (Department of Alternative Energy Development and Efficiency, 2010a). For this reason, the combustion of natural gas majorly contributed to CO_2 and NO_x emissions from the power sector (Figs. 2 and 3). Also, the power generation sector emitted 54% of SO_2 emission in 2010, while 42% and 3% of total SO_2 emission came from manufacturing and transportation sectors, respectively. The coal-fired power plant in Thailand is a major source of SO_2 emissions from power generation (Fig. 4). However, one major coal-fired power plant in Thailand has already been equipped with flue-gas desulfurization (FGD) equipment that removes SO_2 emission from the exhaust flue gases. Therefore, SO_2 emissions from power generation are not that high compared to CO_2 emissions.

At the same time, the transportation sector is an important emitter of NO_x emissions (Fig. 3). The transportation sector emitted 30% of total NO_x emissions in 2010, whereas the electricity generation, manufacturing, others, and residential and commercial sectors shared 28%, 22%, 18% and 4% of total NO_x emissions, respectively (Fig. 3). The transportation sector is one of the fuel oil consumptive sectors, so the combustion of oil generates not only NO_x emissions, but also CO_2 emissions. The increased use of nitrogen based fertilizers in agriculture as well as the oil consumption in the construction and mining sectors contribute to NO_x emissions from others sector (Fig. 3). Moreover, manufacturing is an energy consumptive sector that heavily replies on electricity consumption, oil, coal, and lignite. Many industrial processes emit CO_2 through fossil fuel combustion. Several processes also produce CO_2 emissions through chemical reactions that do not involve combustion. Example include: the production and consumption of mineral products such as cement, the production of metals such as iron and steel. Besides, the combined combustion of coal and lignite in the basic metals, paper products and printing and non-metallic sectors is the main source of SO_2 emissions. Therefore, manufacturing is one of the important sources of CO_2, NO_x and SO_2 emissions.

Most of the emissions of greenhouse gases and aerosols are a consequence of fossil fuel usage to satisfy our growing energy needs (James and Dan, 2002). The main impact from rising CO_2 levels is warmer temperatures on a global scale. SO_2 and NO_x emissions contribute to acid deposition which causes adverse effects on aquatic ecosystems and damage to forests. SO_2 emissions also exacerbate respiratory illnesses and heart diseases, particularly in children and the elderly (James and Dan, 2002). NO_x contributes to the formation of secondary inorganic particulate matter which irritates and damages the lungs (United Nations Economic Commission for Europe, 2013). All emissions from fossil fuel combustion have negative impacts on the environment and human health; therefore, it is necessary to promote energy conservation and emission reduction from the major sectors such as electricity generation, road transportation, and other manufacturing sectors which emit large pollution emissions.

For the transportation sector, fuel switching should be adopted in both passenger and freight transports, including small vehicles, large vehicles and buses, by switching the fuel from oil to compressed natural gas (CNG) or liquefied petroleum gas (LPG). The technological improvement in CNG or LPG engine would result in an energy savings of 30% in Thailand's transportation sector (Pongthanaisawan *et al.*, 2007). Increasing public transportation systems, especially the Metropolitan Rapid Transit (MRT) and Bangkok Mass Transit System (BTS) in Bangkok can reduce future energy requirements and CO_2 emissions in 2020 by 635 thousand ton of oil equivalent (ktoe) and 2024 ktoe, respectively (Tanatvanit *et al.*, 2003). The investment of advanced technologies in the automobile industry such as hybrid cars (plug-in) plays an important role in reducing energy consumption and pollutant air emissions in the long run. Since the market for environmentally friendly cars is growing, eco-cars industry in Thailand should not only focus on the energy savings, but also should be promoted by tax reduction incentives (Winyuchakrit *et al.*, 2011). Moreover, the Thai government needs to set up policy measures aimed at replacing older engine vehicles with new vehicles equipped with advanced technologies, and complying with the new

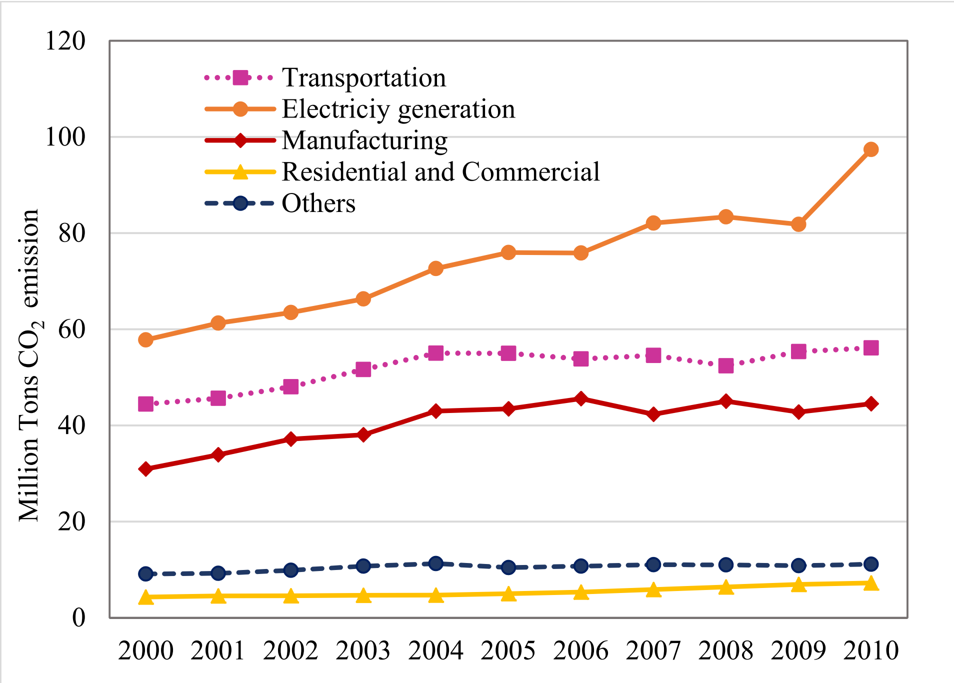

Fig. 2. CO_2 emission from major economic sectors in 2000, 2005 and 2010.

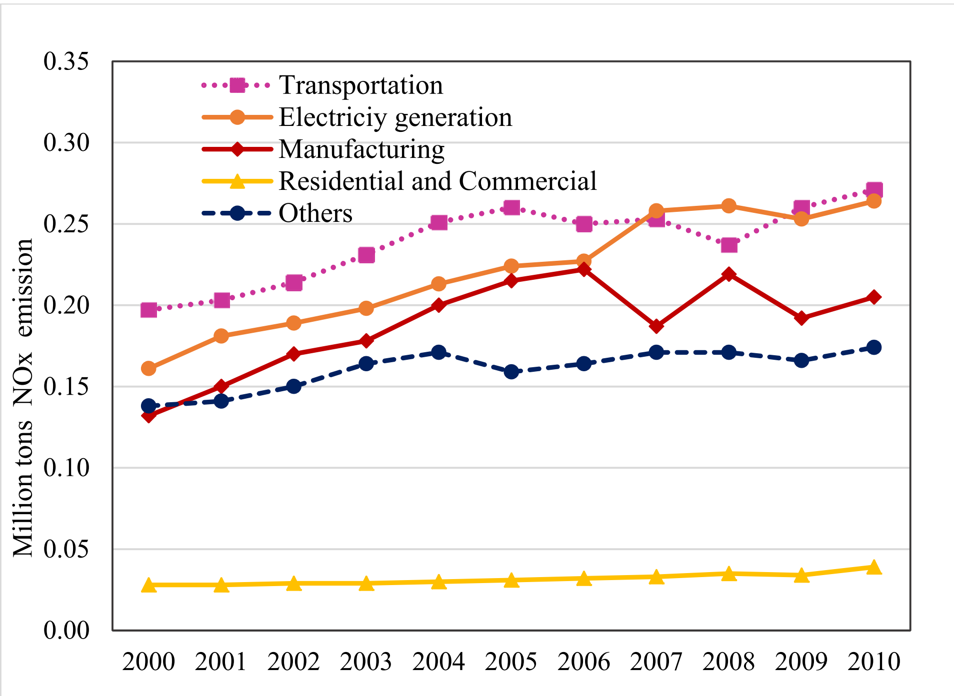

Fig. 3. NO_x emission from major economic sectors in 2000, 2005 and 2010.

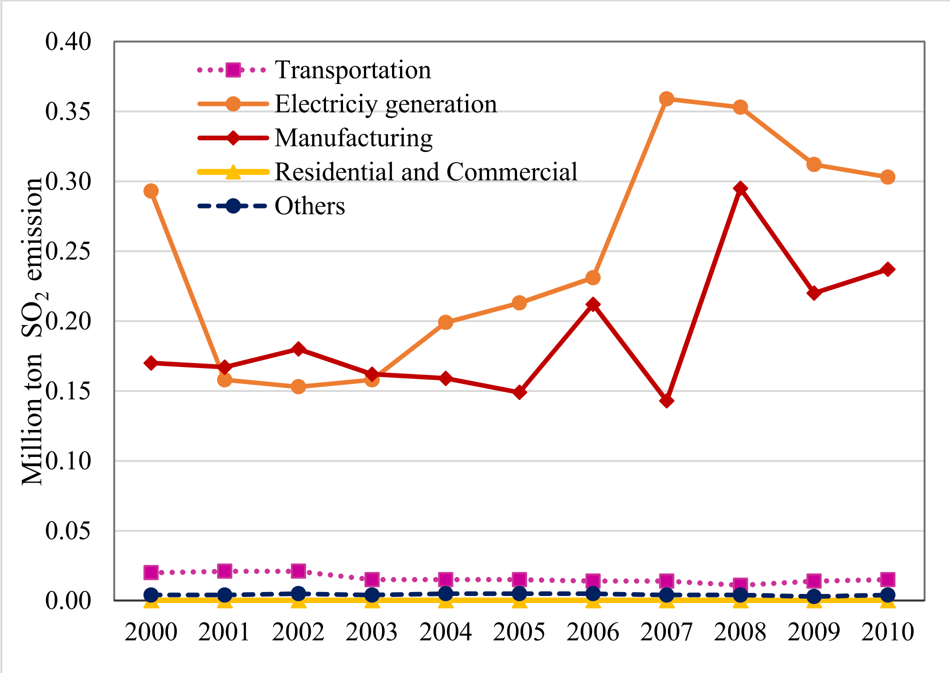

Fig. 4. SO_2 emission from major economic sectors in 2000, 2005 and 2010.

regulations or retrofitting the engines with appropriate emission control devices.

The electricity generation sector is the major energy consumptive and the highest energy-intensive sector among the 19 sectors in 2010. In order to lessen the energy consumption and mitigate CO_2, SO_2, and NO_x emissions from Thailand's power industry, improvement for electricity transmission, distribution and convention processes would save the electricity efficiency, investment should be made in advanced combustion technologies as well as the new technologies for renewable power generation. Nonetheless, Thailand is an agriculture-based country; the wastes from agricultural activities such as rice husk and bagasse can be utilized as energy sources to produce heat and power, hence, biomass is one of the most prospective renewable in Thailand. Moreover, the government should undertake an environmental impact assessment (EIA) for proposed nuclear power plant construction (Ministry of Energy, 2015) as well as educate people about the benefits of using nuclear power, and the possible consequences of their adverse effects in the future.

Direct and Indirect of Energy Consumption

The percentage of direct and indirect effects on energy consumption for 19 sectors are shown in Table 7. Each of road transportation, petrochemical industry, mining and quarrying, non-metallic products, and wood and wood products sectors had a high share of direct energy consumption. In contrast, the construction, machinery, other manufacturing, wholesale trade and services, textile and leather, and food and tobacco sectors were the dominant sectors with a large ratio of indirect energy consumption. According to the inter-industry linkages results, these five sectors had a large backward linkage effect, and a relatively small forward linkage effect. So, all of them played an important role in consuming other commodities input. This greatly affected the indirect energy consumption in these five sectors. The direct energy consumption of the electricity generation (76%) was higher than the indirect energy consumption (24%) (Table 7). However, results also reveal that the total energy intensity of $8{,}731 \times 10^7$ kcal million $US\$^{-1}$ from 19 sectors consisted of a direct and indirect energy intensity of $4{,}083 \times 10^7$ kcal million $US\$^{-1}$ and $4{,}648 \times 10^7$ kcal million $US\$^{-1}$, respectively (Table 5). In other words, indirect energy intensity contributed over 53% of the total energy intensity for 19 sectors, whereas 47% of total energy intensity came from direct energy.

Direct and Indirect of CO_2 Emission

Table 8 shows the percentage share of the direct and indirect CO_2 emission for 19 sectors. Regarding direct CO_2 emission, the amount of CO_2 generated from fossil fuel combustion depends primarily on fuel type and quantity. Meanwhile, the indirect CO_2 emissions are defined as the emissions that are a consequence of the activities which can occur at the sources owned or controlled by other related activities (Sodsai and Rachdawong, 2012). In other words, the emission generated from the fuel combustion source is not counted as an indirect emission. Results show that the machinery, construction, wholesale trade, and services, other manufacturing, and textile and leather and food and tobacco sectors were the major sectors with a huge indirect CO_2 emission. Based on linkage effect analysis, these sectors had a high backward linkage effect, which means these sectors had more strength in adsorbing products of related industries. Hence, indirect CO_2 emissions played significant role in these sectors. On the other hand, important sectors with a large proportion of direct CO_2 emission include: the

Table 7. Direct/indirect effects of energy consumption for the 19 aggregated sectors in Thailand.

Sector	2010	
	Direct effect	Indirect effect
1. Agriculture and Forestry	29%	71%
2. Petroleum and Natural Gas Extraction	69%	31%
3. Mining and Quarrying	77%	23%
4. Food and Tobacco	21%	79%
5. Textile and Leather	12%	88%
6. Paper Products and Printing	63%	37%
7. Wood and Wood Products	74%	26%
8. Chemical Industries	19%	81%
9. Petrochemical Industry	80%	20%
10. Basic Metals	37%	63%
11. Non-metallic Products	74%	26%
12. Electricity Generation and Gas Services	76%	24%
13. Machinery	1%	99%
14. Construction	1%	99%
15. Other Manufacturing	8%	92%
16. Road Transportation	83%	17%
17. Other Transportation	40%	60%
18. Wholesale Trade and Services	3%	97%
19. Unclassified	22%	78%

Table 8. Direct/indirect effects of CO_2 emission for the 19 aggregated sectors in Thailand.

Sector	2010	
	Direct effect	Indirect effect
1. Agriculture and Forestry	32%	68%
2. Petroleum and Natural Gas Extraction	72%	28%
3. Mining and Quarrying	88%	12%
4. Food and Tobacco	30%	70%
5. Textile and Leather	23%	77%
6. Paper Products and Printing	67%	33%
7. Wood and Wood Products	81%	19%
8. Chemical Industries	29%	71%
9. Petrochemical Industry	78%	22%
10. Basic Metals	46%	54%
11. Non-metallic Products	77%	23%
12. Electricity Generation and Gas Services	74%	26%
13. Machinery	2%	98%
14. Construction	4%	96%
15. Other Manufacturing	9%	91%
16. Road Transportation	86%	14%
17. Other Transportation	46%	54%
18. Wholesale Trade and Services	6%	94%
19. Unclassified	31%	69%

road transportation, mining and quarrying, nonmetallic products, wood and wood products, and petrochemical industry. However, the direct CO_2 emissions from electricity generation came from the fuel combustion effect, whereas the construction of power plant, and the transmission of electricity probably contributed to the indirect CO_2 emission. Additionally, results show that the total CO_2 intensity 24,971 ton CO_2 million US^{-1} from 19 sectors shared a direct energy intensity 11,957 ton CO_2 million US^{-1}, and indirect energy intensity 13,014 ton CO_2 million US^{-1} (Table 6). That is, the indirect CO_2 intensity accounted for more than 52% of the total CO_2 intensity for 19 sectors, whereas direct CO_2 intensity was 48% of total CO_2 intensity.

Because of fossil fuel combustion being connected to CO_2 emissions, the important sectors with highest direct and indirect energy consumption and CO_2 emissions show similar result (Tables 7 and 8). In order to cope with the large proportions of indirect energy consumption and CO_2 emission from construction, the improvement of energy use in the building or construction sector should be emphasized. For example, the building insulation, which focuses on the materials to limit heat transfer through wall (Santisirisomboon *et al.*, 2003), should be improved. Sustainable design of buildings in Thailand should be promoted in the future to reduce the environmental impact of other types of construction. Moreover, the food and tobacco and textile and leather sectors are classified as agro-industry or agro-processing, which refers to the activities involved in the transformation, preservation, and preparation of agricultural production for intermediate or final consumption (Food and Agriculture Organization of the United Nations, 1997; United Nations Statistic Division, 2016). The functionality of both sectors involves many sectors such as the agriculture and forestry, machinery, electricity generation, and gas services sectors. However, the important keys for indirect emissions are the textile and leather, and food and tobacco producers, who are in charge of managing their needs. Therefore, the textile and leather and food and tobacco producers could save energy consumption and cut CO_2 emissions by improving the electricity efficiency of their production processes.

In summary, energy consumption is a strong foundation of sustainable development, as revealed through the significance of the electric power industry in the Thai economy. It is urgent to reduce energy consumption and pollution emission of Thailand's electricity generation sector. Moreover, our finding demonstrated that the total indirect energy intensity and total indirect CO_2 intensity from the aggregated 19 sectors in 2010 were 53% and 52%, respectively. Therefore, the fact that the source contributed to indirect energy intensity and CO_2 intensity is significant, and it should not be overlooked. Accordingly, the Thai government should pay attention to the sectors with higher indirect intensity such as the construction, machinery, and wholesale trade and services sectors.

CONCLUSIONS

This study aims to estimate the inter-industry linkage of 19 economic-based sectors for years 2000, 2005, and 2010. The forward and backward linkage effects of the electricity generation sector were calculated through the sensibility index of dispersion and the power index of dispersion. Results reveal that the electricity generation sector significantly influenced other industries in the Thai economy, but it was weak in promoting other industries' output. Moreover, an industry with a large forward linkage effect played an important role in serving other industries; such as petroleum and natural gas extraction, mining and quarrying, basic metal sectors. On the other hand, the sectors with a high backward linkage effect had a high dispersion power index in absorbing other industry's products; such as in the machinery, wholesale trade and services, food and tobacco sectors.

The energy and CO_2 multiplier was adopted to quantify the energy intensity and CO_2 intensity of the 19 sectors in our study. We found that the electricity generation and gas services sector was the most dominant energy consumer and the largest CO_2 emission source in 2010, followed by the petrochemical industry and road transportation sectors. Results have shown that the electricity generation and gas services sector was the highest direct energy intensive and highest total energy intensive sector; this was followed by the road transportation and petrochemical industry sectors. However, the largest direct CO_2 emission and total CO_2 intensive sectors were the electricity generation and gas services, road transportation and non-metallic products. Therefore, the electricity generation and gas services was the highest energy intensive and CO_2 intensive among 19 sectors in 2010 with 1,770 $\times 10^7$ kcal million US^{-1} and 3,521 ton CO_2 million US^{-1}, respectively. Besides, the electricity generation sector is an important emitter of CO_2 and SO_2 emissions, whereas transportation and others sectors are a main emitter of NOx emission.

We further investigated the direct and indirect effects on energy consumption and CO_2 emissions. Findings indicated that the total indirect energy intensity and indirect CO_2 intensity in 2010 were 4,648 $\times$ 10^7 kcal million US^{-1} and 13,014 ton CO_2 million US^{-1}, respectively. Also, both energy and CO_2 indirect intensities accounted for more than 50% of the total intensity. As a result, the indirect energy intensity and indirect CO_2 intensity played significant roles in Thai's industry. Hence, the indirect effects of both energy and CO_2 emissions from the machinery, construction, wholesale trade, and services, other manufacturing, textile and leather, and food and tobacco sectors should be noticed. Suggestions for reducing the indirect energy consumption and CO_2 emission include: (1) Fossil fuel consumption in a major upstream of food and tobacco, and textile and leather should adjust toward a lower energy intensity and low-carbon emissions. For example, natural gas should be used as the fuel source in agriculture instead of relying on oil and petroleum products. Besides, improving the electricity efficiency of food and tobacco, and textile and leather production processes would save energy consumption and reduce CO_2 emission. (2) Sustainable design of buildings facilities to minimize energy consumption should be improved, for example the building insulation, cooling devices, and lighting.

Regarding the policy implementation in Thailand, Thailand Power Development Plan 2015-2036 (PDP 2015) aims to reduce dependency on natural gas, to increase the portion of renewable electricity generation, reduce the CO_2 intensity from 0.506 $kgCO_2\ kwh^{-1}$ in 2013 to 0.319 $kgCO_2\ kwh^{-1}$ in 2036. In addition, PDP has proposed several nuclear power plants for the long term (Ministry of Energy, 2015). However, some additional suggestions can be made. For example, electricity in transmission, distribution and conversion processes should be improved in order to increase the electricity efficiency along the path from generated fuel to final delivery to customers, the EIA program should be effectively applied to the proposed nuclear power plant construction in Thailand.

In this study, we find that the Input-Output Analysis is one of the most useful methods to identify the interrelationship among industries, and access both direct and indirect effects of energy consumption and emission pollution. Also, multiplier analysis is used to measure both direct and indirect intensity effects of energy consumption and emissions. Consequently, the methodology used herein can be applied to other industries, and they can also provide a guide for governments to evaluate relative economic contribution and environmental impact on energy consumption and CO_2 emission.

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REFERENCES

Ali, Y. (2015). Measuring CO_2 emission linkages with the hypothetical extraction method (HEM). *Ecol. Indic.* 54: 171–183.

Bekhet, H. A. and Yasmin, T. (2014). Assessment of the global financial crisis effects on energy consumption and economic growth in Malaysia: An input–output analysis. *Int. Econ.* 140: 49–70.

Butnar, I. and Llop, M. (2007). Composition of greenhouse gas emissions in Spain: An input–output analysis. *Ecol. Econ.* 61: 388–395.

Climate Stewards. (2015). What Is COP21?, https://www.climatestewards.org/cop21/, Last Access: 11 June 2016.

Cui, L.B., Peng, P. and Zhu, L. (2015). Embodied energy, export policy adjustment and China's sustainable development: A multi-regional input-output analysis. *Energy* 82: 457–467.

De Mesnard, L. (2009). On the Fallacy of Forward Linkages: A Note in the Light of Recent Results: LEG, Laboratoire d'Economie et de Gestion, CNRS, Université de Bourgogne.

Department of Alternative Energy Development and Efficiency (2005). Thailand Energy Situation 2005, Ministry of Energy, Bangkok,Thailand, pp. 13–14, 29–30.

Department of Alternative Energy Development and Efficiency (2010a). Electric Power in Thailand 2010, Ministry of Energy Bangkok,Thailand, pp. 23–25.

Department of Alternative Energy Development and Efficiency (2010b). Thailand Energy Situation 2010, Ministry of Energy Bangkok,Thailand, pp. 13–14, 30–31.

Department of Alternative Energy Development and Efficiency (2014a). Energy Balance in Thailand 2014, Ministry of Energy, Bangkok,Thailand, pp. 21–34.

Department of Alternative Energy Development and Efficiency (2014b). Thailand Energy Efficiency Situation, Ministry of Energy, Bangkok,Thailand, pp. 21–25.

Food and Agriculture Organization of the United Nations. (1997). The Agroprocessing Industry and Economic Development http://www.fao.org/docrep/w5800e/w5800e12.htm, Last Access: 5 January 2016.

Ghosh, A. (1958). Input-output approach in an allocation system. *Economica* 25: 58–64.

Hirschman, A.O. (1958). *The Strategy of Economic Development*. Yale University Press New Haven.

International Energy Agency (2003). Energy Statistics of Non-Oecd Countries 2000-2001, International Energy Agency, OECD, Paris, France, pp. 397–399.

International Energy Agency (2008). Energy Statistics of Non-Oecd Countries 2005-2006, International Energy Agency, OECD, Paris, France, pp. 406–408.

International Energy Agency (2012). Energy Statistics of Non-Oecd Countries 2009-2010, International Energy Agency, OECD, Paris, France, pp. 410–412.

IPCC (2006). 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories, Inter-Govermental Panel on Climate Change.

James, A.F. and Dan, S.G. (2002). *Energy and the Environment*. Oxford University Press, New York.

Kofoworola, O.F. and Gheewala, S.H. (2008). An input–output analysis of Thailand's construction sector. *Constr. Manage. Econ.* 26: 1227–1240.

Kwangmoon, K., Secretario, F. and Trinh, B. and Hidefumi, K. (2011). Developing a Bilateral Input-Output Table in the Case of Thailand and Vietnam: Methodology and Applications, 19th International Input-Output Conference. Alexandria, Virginia, USA.

Lenzen, M. (2003). Environmentally important paths, linkages and key sectors in the Australian economy. *Struct. Change Econ. Dyn.* 14: 1–34.

Leontief, W. (1936). Quantitative input and output relations in the economic systems of the United States. *Rev. Econ. Stat.* 18: 105–125.

Leontief, W. (1970). Environmental repercussions and the economic structure: An input-output approach. *Rev. Econ. Statist.*: 262–271.

Li, P., Pan, S.Y., Pei, S., Lin, Y.J. and Chiang, P.C. (2016). Challenges and perspectives on carbon fixation and utilization technologies: An overview. *Aerosol Air Qual. Res.* 16: 1327–1344.

Lin, S.J. and Chang, Y.F. (1997). Linkage Effects and environmental impacts from oil consumption industries in Taiwan. *J. Environ. Manage.* 49: 393–411.

Lin, S.J., Liu, C.H. and Lewis, C. (2012). CO_2 emission multiplier effects of Taiwan's electricity sector by input-output analysis. *Aerosol Air Qual. Res.* 12: 180–190.

Lin, S.J., Beidari, M. and Lewis, C. (2015). Energy consumption trends and decoupling effects between carbon dioxide and gross domestic product in South Africa. *Aerosol Air Qual. Res* 15: 2676–2687.

Liou, J.L., Chiu, C.R., Huang, F.M. and Liu, W.Y. (2015). Analyzing the relationship between CO_2 emission and economic efficiency by a relaxed two-stage dea model. *Aerosol Air Qual. Res.* 15: 694–701.

Liu, C.H., Lin, S.J. and Lewis, C. (2013). Evaluation of NO_x, SO_x and CO_2 emissions of Taiwan's thermal power plants by data envelopment analysis. *Aerosol Air Qual. Res.* 13: 1815–1823.

Machado, G., Schaeffer, R. and Worrell, E. (2001). Energy and carbon embodied in the international trade of Brazil: An input–output approach. *Ecol. Econ.* 39: 409–424.

Miller, R.E. and Blair, P.D. (1985). *Input-Output Analysis: Foundations and Extensions*. Prentice-Hall, Englewood

Cliffs.

Miller, R.E. and Lahr, M.L. (2001). *A Taxonomy of Extractions. Regional Science Perspectives in Economic Analysis: A Festschrift in Memory of Benjamin H. Stevens*. Amsterdam.

Miller, R.E. and Blair, P.D. (2009). *Input-Output Analysis: Foundations and Extensions*. Cambridge University Press, New York.

Ministry of Energy (2011). 20-Year Energy Efficiency Development Plan (2011-2030), Ministry of Energy, Bangkok, Thailand, pp. 1–6.

Ministry of Energy (2015). Thailand Power Development Plan 2015-2036 Energy Policy and Planning, Ministry of Energy, Bangkok, Thailand, pp. 5–10, 29–32, 44–45.

National Economic and Social Development Board (2000). Input-Output Table of Thailand 2000, Office of the National Economic and Social Development Board, Bangkok, Thailand.http://www.nesdb.go.th/Portals/0/eco_datas/account/io/data/2000/I-O%20Book%202000.pdf, Last Access: 16 June 2014.

National Economic and Social Development Board (2005). Input-Output Table of Thailand 2005, Office of the National Economic and Social Development Board Bangkok,Thailand.http://www.nesdb.go.th/Portals/0/eco_datas/account/io/data/2005/I-O%20Book%202005.pdf, Last Access: 20 July 2014.

National Economic and Social Development Board (2010). Input-Output Table of Thailand 2010, Office of the National Economic and Social Development Board, Bangkok, Thailand.http://www.nesdb.go.th/Portals/0/eco_datas/account/io/data/2010/IO%202010%20at%20purchaser%20price%20(Preliminary).xls, Last Access: 24 October 2015.

Park, J.Y. (2007). The Supply-Driven IO Model a Reiniterpretation and Extension, 46th Annual Meeting of the Western Regional Science Association. Newport Beach, California, USA.

Pongthanaisawan, J., Sorapipatana, C. and Limmeechokchai, B. (2007). Road transport energy demand analysis and energy saving potentials in Thailand. *Asian J. Energy Environ.* 8: 49–72.

Rasmussen, P.N. (1956). *Studies in Inter-Sectoral Relations*. E. Harck, Amsterdam: North-Holland.

Santisirisomboon, J., Limmeechokchai, B. and Chungpaibulpatana, S. (2003). Least cost electricity generation options based on environmental impact abatement. *Environ. Sci. Policy* 6: 533–541.

Smith, P., Smith, P. and Morrison, W. (2006). *Simulating the Urban Economy: Experiments with Input-Output Techniques*. Routledge, Taylor and Fransic group, Abingdon Oxfordshire, UK, .

Sodsai, P. and Rachdawong, P. (2012). The current situation on CO_2 emissions from the steel industry in Thailand and mitigation options. *International Journal of Greenhouse Gas Control* 6: 48–55.

Tanatvanit, S., Limmeechokchai, B. and Chungpaibulpatana, S. (2003). Sustainable energy development strategies: Implications of energy demand management and renewable energy in Thailand. *Renewable Sustainable Energy Rev.* 7: 367–395.

Tonn, B. (2003). An equity first, risk-based framework for managing global climate change. *Global Environ. Change* 13: 295–306.

United Nations Economic Commission for Europe (2013). Pollutant Emissions in the Transportation Sector http://www.unece.org/fileadmin/DAM/trans/doc/2013/wp29grpe/GRPE-66-09-Rev.1.pdf, Last Access: 22 April 2016.

United Nations Framework Convention on Climate Change (2015). Thailand's Intended Nationcally Determined Contribution (INDC), http://www4.unfccc.int/submissions/INDC/Published%20Documents/Thailand/1/Thailand_INDC.pdf, Last Access: 14 January 2016.

United Nations Statistic Division (2016). International Standard Industrial Classification of All Economic Activities, Rev.4, http://unstats.un.org/unsd/cr/registry/regcst.asp?Cl=27, Last Access: 5 January 2016.

Winyuchakrit, P., Limmeechokchai, B., Matsuoka, Y., Gomi, K., Kainuma, M., Fujino, J. and Suda, M. (2011). Thailand's low-carbon scenario 2030: Analyses of demand side CO_2 mitigation options. *Energy. Sustainable Dev.* 15: 460–466.

World Bank Group. (2015). World Development Indicators, Last Access: 5 December 2015.

Wright, D.J. (1974). 3. Good and services: An input-output analysis. *Energy Policy* 2: 307–315.

Xin, L., Feng, K., Siu, Y.L. and Hubacek, K. (2015). Challenges faced when energy meets water: CO_2 and water implications of power generation in inner mongolia of China. *Renewable Sustainable Energy Rev.* 45: 419–430.

Yoo, S.H. and Yoo, T.H. (2009). The role of the nuclear power generation in the Korean national economy: An input–output analysis. *Prog. Nucl. Energy* 51: 86–92.

Yu, E.S. and Choi, J.Y. (1985). The causal relationship between energy and GNP: An international comparison. *J. Energy Dev.* 10: 2.

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