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Environmental Impacts of Electricity Sector in Taiwan by Using Input-Output Life Cycle Assessment: The Role of Carbon Dioxide Emissions

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ABSTRACT

Electricity has played a critical role in supporting industrial development and economic growth in Taiwan. In this study, input-output analysis is combined with life cycle assessment to evaluate the total environmental impacts (including direct and indirect) of the electricity sector in Taiwan. The results indicate that the environmental impacts of Taiwan's electricity sector increased from 2001 to 2006, and 85% of these are focused on eight related sectors. In addition, "human health" suffers from the most significant environmental impact, followed by "resources", "climate change" and "ecosystem quality". Although direct environmental impacts are significant, especially with regard to climate change, indirect environmental impacts are gradually increasing. Because the electricity sector is linked to many other sectors, there would be an underestimation of CO_2 emissions and other environmental impacts if the indirect effects from the related sectors were omitted from the calculations. These indirect impacts mainly come from the "non-metallic minerals", "petroleum refining products" and "other metals" sectors, and the technology used in these three sectors needs to improve and become more environmentally-friendly. Other suggestions to promote the sustainable development of Taiwan's electricity sector include upgrading energy efficiency, implementing stricter effluent regulatory standards, maximizing energy security with a higher proportion of renewable energy sources, phasing out old fossil fuel plant facilities, seeking international cooperation for CCS technology, and promoting energy-saving by providing economic incentives. This study is of value to the government and relevant industries that are working to identify the total environmental impacts of their energy policies, and to plan mitigation strategies and policy implementations to reduce CO_2 emissions and control pollution.

Keywords: Electricity sector; IO-LCA; Direct and indirect impacts; CO_2 emissions.

INTRODUCTION

Electricity plays a crucial role in modern society and is the lifeline of a country. Its abundant supply and continuous quality enhancement are the foundations of national economic development. In 2010, gross electricity generation reached 247,045 GWh, which was an increase of 7.5% over 229,694 GWh in 2009 (Bureau of Energy, 2011a). Of this total, hydro power contributed 2.9%, thermal power 79.8%, nuclear power 16.9%, and geothermal, solar and wind power 0.4%. Furthermore, the percentage of electricity from thermal power increased considerably from 54% in 1990 to 79.8% in 2010 due to the national "nuclear-free homeland" policy (Bureau of Energy, 2011a). The CO_2 emission from electricity sector in 2010 accounted for 65.7% of total GHG emissions (Bureau of Energy, 2011b). This situation indicates that the electricity sector is the most significant source of CO_2 emissions in Taiwan.

In addition, Taiwan is recognized by the United Nations (UN) as a significant source of greenhouse gas (GHG) emissions and because of this is included in the World Resources Institute's Climate Analysis Indicators Tool (CAIT) - UNFCCC project (World Resource Institute, 2010). Taiwan's emissions of the six greenhouse gases monitored by the UN - carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride - are rising. Although Taiwan is neither a UN member nor a party to the Convention on Climate Change, the country has responded to the post-Kyoto protocol international trends so as to cope with the increasing electricity consumption while also achieving economic growth and sustainable development. Taiwan's Environmental

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Protection Administration (EPA) has requested most sectors and companies to supply details of GHG emissions as part of its bid to join the United Nation's Kyoto climate pact. In order to meet these challenges, methods for assessing environmental impacts have been developed (Finnveden and Moberg, 2005; Ness *et al*., 2007; Finnveden *et al*., 2009). One such prominent method is input-output life cycle assessment (IO-LCA) which integrates input-output analysis (IOA) and life cycle assessment (LCA).

Basically, LCA is a tool to assess the potential environmental impacts and resource consumption throughout a product's lifecycle and to consider all attributes or aspects of natural environment, human health and resources (ISO 14040:2006, 2006). The term 'product' includes both goods and services. In addition, IOA is a field of economics that deals with the connections between industrial sectors and households in a national economy in the form of supply and consumption of goods and services, formation of capital, and exchange of income and labor (Finnveden *et al*., 2009). Based on the combination of LCA and IOA, IO-LCA was developed to compute the cradle-to-gate environmental load of a given activity based on a financial expenditure of an organization.

In this study, IO-LCA is adopted to evaluate the environmental impacts of Taiwan's electricity sector in the years 2001, 2004 and 2006. It can be used to estimate the environmental impacts generated throughout the upstream supply-chain. We consider not only the direct environmental impacts but also the indirect environmental impacts from other related industries in the economy. Previous studies do not specifically calculate the indirect impacts because the difficulty of measuring off-site impacts, or the assumption that these are relatively insignificant component of the total impacts. The innovative way in this study is to combine LCA with IOA to calculate the total environmental impacts. It is important for government and industries (upstream/ downstream) to improve policy implements. The paper is organized as follows: Section one describes the current data and GHG reporting situation for the electricity sector in Taiwan. Section two outlines related IO-LCA studies. Section three describes the integrated IO-LCA method. Section four provides details on the database employed in this study. Section five presents results and discussion. Section six gives the policy implications and suggestions for improving and upgrading Taiwan's energy sector. Section seven is the conclusion.

Literature Review

Life cycle assessment studies often employ not only process analysis but also input-output analysis (Lave *et al*., 1995; Hendrickson *et al*., 1998; Joshi, 1999; Matthews and Small, 2000; Heijungs and Suh, 2002; Lenzen, 2002; Suh and Huppes, 2005; Heijungs *et al*., 2006). Life-cycle inventories calculated using IO-based techniques generally yield more comprehensive results compared to process analysis because the latter systematically truncates inputs from higher upstream production processes due to the setting of system boundaries (Lenzen, 2002; Suh and Huppes, 2005).

Few IO-LCA studies have been conducted with a focus on power generation issues. Voorspools *et al*. (2000) used process-based LCA and IO-LCA to estimate the indirect GHG emissions which related to construction of nuclear plants and wind farms. Their results from two methods are significantly different for nuclear plants, but are effectively the same for wind farms. This is because components of nuclear power plants are more expensive than average products from the other sectors, and the IO-LCA gives an overestimation. In addition, a wind turbine appears to be an average product material-wise or in an economic context. Lenzen and Wachsmann (2004) used tiered hybrid LCA to examine the energy and CO_2 embodied in a particular wind turbine manufactured in Brazil and in Germany. Their results demonstrated the importance of adequately considering the background system of the local economy. Hondo (2005) estimated life cycle GHG emission per kWh of electricity generated for nine different types of power generation systems using a combined method of process analysis and input output analysis. Their results provided valuable information to select power generation technologies from the viewpoint of global warming. Yang *et al*. (2007) evaluated the environmental impacts of 13 electric power plants in Taiwan by LCA. Three scenarios for fuel selection were considered to evaluate the environmental trends related to Taiwan's electric power industry. Results indicate that there are differences in characteristic environmental impact among the 13 power plants. Gas-fired combined cycle generators should be substituted for the coal-fired and oil-fired steam turbine generators to be more environmentally friendly. Odeh and Cockerill (2008) examined life cycle GHG emissions from three types of fossil-fuel-based power plants, namely supercritical pulverized coal (super-PC), natural gas combined cycle (NGCC) and integrated gasification combined cycle (IGCC), with and without carbon capture and storage (CCS). The CO_2 from materials production was estimated by process analysis, while the CO_2 from other processes was estimated using IO table. Results showed that GHG emissions from UK fossil fuel power plants with CCS can be reduced by 75–84% relative to a subcritical PC power plant. Varun *et al*. (2008) quantified the energy use and GHG emissions of three run-of river small hydropower projects in India. The life cycle analysis has been carried out by using the economic input-output technique. Their results showed that the GHG emission varies from 35.3 to 74.9 gCO_{2eq}/kWh. The GHG emissions from small hydro power generation system are less when compared to the conventional type of electricity generation systems. Chao *et al*. (2009) applied IO-LCA to identify the domestic impact generated by the industrial production to fulfill the foreign needs (the loans) and the foreign impact to the domestic consumption in Taiwan (the debts). Their result revealed that for the energy and resource consumption the debts on water is larger than that of the loans, whereas, energy shows different trends. Crawford (2009) presented the results of a life cycle energy and greenhouse emissions analysis of two wind turbines. The embodied energy component was found to be more significant than in previous studies due to the use of an IO-based hybrid embodied energy analysis approach. Ma *et al*. (2009) evaluated the environmental impact of different consumption patterns based on input-output LCA. The differences of consumption patterns of various cities and counties caused the environmental impact to vary as much as 82.8–92.7% of the average values for various impact categories. Wiedmann *et al.* (2010) investigated the effectiveness and suitability of three different hybrid LCA methods to account for the indirect GHG emissions of the wind power sector in UK. They found that IO-LCA is a practical and efficient way to build technology specific processes into a generalized environmental economic modeling framework that will aid in gaining an understanding of magnitude of economy-wide GHG emissions.

Numerous important studies related to characteristics of air pollutants and air quality improvement had been extensively discussed in recent years. Hsieh and Chen (2010) evaluated the characteristics of volatile organic compounds (VOC) and ammonia around industrial parks. Wang *et al.* (2010) evaluated the characteristics of heavy metals emitted from power plants. Abu-Allaban and Abu-Qudais (2011) predicted the air pollutants (dust, SO_2, NO_x and CO) emitted from a modern cement plant in Jordan. Their findings indicated that concentrations of air pollutant are found to be well below the permissible Jordanian Standards for ambient air quality. Fang *et al.* (2011) measured the concentration of As and dry deposition fluxes. Also, issues related to climate change and greenhouse gas (GHG) effects have gained significant notice during the two decades. Lin *et al.* (2012) provided a 42-sector input-output table for the examination of CO_2 emission multiplier effects among various sectors and electric industry in Taiwan.

METHODOLOGY

Input-Output Analysis (IOA)

As mentioned before, IO-LCA, which integrates LCA and IOA, consists of a matrix of economic data and a matrix of sector level environmental coefficients. The economic data include the inputs from all sectors of the economy into all other sectors and the distribution of each sector's output throughout the economy. The basic framework of input-output study was established by Wassily W. Leontief (Leontief, 1970), for which he received the Nobel Prize in 1973. This top-down approach is based on the relationships between input materials and output products. The interdependencies across different sectors of the economy are represented by a set of linear equations to describe quantitatively the industrial structure and inter relationships.

Considering the advantage of a country's economic input-output tables (I-O table), most national statistical authorities have compiled I-O table as a part of national accounts over 40 years. I-O table was developed originally for the application of an economic sector's transaction, then it turned into an effective tool for LCA practitioners to cope with environmental economic events (Leontief, 1970). The basic I-O table (Table 1) is composed of several matrices, such as the intermediate demand matrix $\mathbf{[X_{ij}]}$, the final demand matrix $\mathbf{[F_i]}$, the total output matrix $\mathbf{[T_i]}$, the primary input matrix $\mathbf{[O_j]}$ and the total input matrix $\mathbf{[X_j]}$.

Based on general equilibrium theory, the total demand equals intermediate demands plus final demands, and also equals the total supply that is the sum of domestic production ($\mathbf{[X_i]}$) and imports ($\mathbf{[P_i]}$). It can be expressed as the following:

$$[W_i] + [F_i] = [P_i] + [X_i] = [T_i] \tag{1}$$

$$\sum X_{ij} + F_i = \sum a_{ij} X_j + F_i = P_i + X_i \tag{2}$$

$$X_i = \sum a_{ij} X_j + F_i - P_i \quad (a_{ij} = X_{ij}/X_j) \tag{3}$$

The element a_{ij} is the input coefficient (or technical coefficient) and represents the monetary value of input required from sector i to produce one dollar worth of output for sector j (i = 1...n, and j = 1...n). Eq. (3) also can be written:

$$X = AX + (F - P) \tag{4}$$

$$X = (I - A)^{-1}(F - P) \tag{5}$$

where **X** represents the vector of total economic outputs of the sectors. **I** is the identity matrix. **A** is the technical coefficient matrix. $\mathbf{(I - A)^{-1}}$ represents the Leontief inverse matrix. **(F – P)** represents the exogenous change in final demand for the output of these sectors.

Input-Output Life Cycle Assessment (IO-LCA)

Using the general formula shown in Eq. (6), economy-wide environmental emissions for the arbitrary final outputs **X** have been calculated as:

$$\begin{aligned} Q &= RX \\ &= R(I - A)^{-1}(F - P) \end{aligned} \tag{6}$$

Table 1. Basic input-output table.

	Intermediate demands (1…j…n)	Sum of intermediate demands	Final demands	Total outputs	Supply	
					domestic production	imports oversea
Intermediate inputs (1…i...n)	$[X_{ij}]$	$[W_i]$	$[F_i]$	$[T_i]$	$[X_i]$	$[P_i]$
Sum of intermediate inputs	$[Y_j]$					
Primary inputs	$[O_j]$					
Total inputs	$[X_j]$					

Note: Leontief (1970); the Accounting Office of Executive Yuan in Taiwan (2004).

where **Q** is the sum of direct and indirect environmental inventory. **R** is the direct pollutant emissions for each dollar of output in each sector (Lin and Chang, 1997).

IO-LCA is according to the prerequisite that unit economic input of one sector links to economic outputs of many other sectors. The researcher does not need to collect data from production processes because the data is included by using I-O table. In addition, the I-O table include the interconnection of economic sectors and industries, and the environmental impact calculated for a sector would contain its complete supply chain (Koellner *et al*., 2007). Up to the present, the IO-LCA approach has been developed toward a part of hybrid analysis (Udo de Haes *et al*. 2004), but it is still more suitable than process LCA for some other purposes (Hendrickson *et al*., 2006). The European Commission's Integrated Product Policy (Commission of the European communities, 2003) has determined that the IO-LCA is the most suitable approach to identify the environmental impact of a product's life cycle. However, the main shortcoming of the IO-LCA is that all products in I-O table are identified as an average product of the covering sector. A sector contains many products for which the price per energy consumption is not necessarily the same. Therefore, the results of IO-LCA are often not suitable for a specific case study (Bilec *et al*., 2010). Another shortcoming is that the relationship between price and environmental impact is linear; this is not always true. Moreover, activities associated with final consumers, such as energy for product use or wastes of product disposal, are not included (Lave *et al*., 1995).

Life Cycle Impact Assessment

The "IMPACT 2002+" impacts assessment method was used in this study due to not only a discussion with engineers of Taiwan Power Company (TPC), but also considering IMPACT 2002+ combines the advantages of another two methods including Eco-indicator 99 and CML. This method's impact classification and weighting factors are more representative of the real condition of Taiwan's electricity sector. The IMPACT 2002+ method proposes a feasible implementation of a combined midpoint/damage approach, linking all types of life cycle inventory results via 14 midpoint categories (human toxicity, respiratory effects, ionizing radiation, ozone layer depletion, photochemical oxidation, aquatic ecotoxicity, terrestrial ecotoxicity terrestrial acidification/nutrification, aquatic acidification, aquatic eutrophication, land occupation, global warming, non-renewable energy, and mineral extraction) to four damage categories (Jolliet *et al*. 2003). However, the damage factors of aquatic acidification and aquatic eutrophication are under development in IMPACT 2002+ version 2.1 (Jolliet *et al*., 2003) in SimaPro 7.1 software.

The IMPACT 2002+ method includes four calculated steps, characterization, damage assessment, normalization and evaluation. It combines the advantages both from midpoint-based indicators (Guinée *et al*., 2002) and from damage-based methodologies (Goedkoop and Spriensma, 2000). In addition to this combined midpoint/damage structure, scientific challenges of the impact assessment including human toxicity and ecotoxicity were also included. All of the human health related categories can be expressed in disability adjusted life years (DALY). In 2012, the latest IMPACT 2002+ method version Q2.2 was released (Humbert *et al*. 2012). The damage factors of aquatic acidification and aquatic eutrophication are preliminary defined. Since we use SimaPro 7.1 to complete the environmental impact calculation in this study, the damages of aquatic acidification and aquatic eutrophication are excluded. The detail information of IMPACT 2002+ method could be viewed in the following documents (Jolliet *et al*., 2003, Humbert *et al*., 2005, Humbert *et al*., 2012).

DATA CONSOLIDATION

The I-O table was originally compiled by the Accounting and Statistics Office of Executive Yuan in Taiwan. It is released and revised every 2–3 years for consistency with the industry, commerce and service census or production and cost survey. The I-O table used in this study includes a 160-sector table for 2001 (Directorate-General of Budget, Accounting and Statistics, 2004), a 161-sector table for 2004 (Directorate-General of Budget, Accounting and Statistics, 2007), and a 166-sector table for 2006 (Directorate-General of Budget, Accounting and Statistics, 2009). All sectors are classified according to the most recent base year input-output table whenever the table is prepared.

For energy consumption, the annual aggregate information on energy products with flows from supply, transformation, final consumption by sector and major industries is adopted the data from the ''Taiwan Energy Balance Sheets'' (Bureau of Energy, 2011c). Furthermore, the CO_2 emissions of various sectors were estimated according to the IPCC guidelines (IPCC, 2006). For other environmental emissions, the difficulties mainly lie in the lack of relevant statistics in Taiwan. The missing inventory estimation tool (MIET) 3.0 version in SimaPro 7 program is used to estimate the environmental emissions of the sectors. MIET 3.0 using input-output techniques has detailed table and environmental data (PRé Consultants, 2008). Toxic emissions by the establishments under the threshold are estimated. Nutrients emission and natural resources consumption has also been surveyed. Land use category is newly added.

RESULTS AND DISCUSSION

In this study, we evaluate the electricity sector's direct and indirect environmental impacts by IO-LCA. Based on the I-O table's framework, more than one hundred sectors have financial linkages with the electricity sector, and can not be presented specifically for all. Under this consideration, the following results are only shown for the eight most important sectors which totally account for more than 85% of the environmental impacts of the electricity sector. These sectors include coal products, electricity, non-metallic minerals, other chemical materials, other metals, petroleum refining products, primary iron and steel products, and special-purpose machinery (Table 2).

The environmental damages from the Taiwan electricity sector in 2001, 2004 and 2006 are given in Table 3, and then the damage values are normalized by IMPACT 2002+ method (Fig. 1). According to the results from Table 3, the electricity sector comprises the main part of human health damages. It has 114,523, 128,846 and 153,110 DALY in 2001, 2004 and 2006, and separately accounts for 66%, 58% and 42% of each year's total human health damage. Moreover, the sectors of non-metallic minerals and other metals are the other two major sources. The proportions of each of two sectors are from 8% to 15% of each year's total health damages.

Table 3 also shows that electricity sector itself is the largest GHGs contributor to the climate change category. The CO_2 emissions increase in quantity from 125 Mton in 2001 to 168 Mton in 2006, but the percentage of each year's total emissions decreases from 92% in 2001 to 83% in 2006. In addition, the second major CO_2 emission source is the sector of petroleum refining products, and the CO_2 emissions increase from 4 Mton (3%) in 2001 to 10 Mton (5%) in 2006. For the resource category, almost 90% of the whole resource consumption is resulted from the sum of the electricity sector and the petroleum refining products sector.

Table 2. The definition of eight important sectors.

Sector	Definition
Coal products	Products of petroleum and coal
Electricity	Electric services
Non-metallic minerals	Nonmetallic mineral services and miscellaneous
Other chemical materials	Industrial inorganic and organic chemicals
Other metals	Copper, magnesium, and related products
Petroleum refining products	Oil products and residual products of petroleum refining
Primary iron and steel products	Products of iron and steel forgings
Special-purpose machinery	Special industry machinery

Ref: Directorate-General of Budget, Accounting and Statistics, 2010.

Table 3. Environmental damage of electricity sector in Taiwan.

	Year	Climate Change	Resources	Human Health	Ecosystem Quality
		(ton CO_2)	(GJ)	(DALY)	(10^3 PDF*m^2*yr)
Coal products	2001	254,768	33,744,551	1,036	274,538
	2004	302,036	40,005,333	1,228	325,474
	2006	501,959	66,485,559	2,041	540,911
Electricity	2001	125,521,137	1,163,316,252	114,523	25,559,985
	2004	141,220,281	1,308,814,211	128,846	28,756,817
	2006	167,814,048	1,555,282,351	153,110	34,172,130
Non-metallic minerals	2001	2,555,503	36,922,617	13,468	3,058,490
	2004	4,870,626	70,372,153	25,669	5,829,286
	2006	8,506,177	136,710,349	53,638	20,146,814
Other chemical materials	2001	415,444	24,888,785	4,309	4,089,554
	2004	378,385	22,668,614	3,924	3,724,751
	2006	814,644	48,804,385	8,449	8,019,201
Other metals	2001	135,857	1,602,407	14,088	22,684,329
	2004	277,660	3,274,937	28,793	46,361,351
	2006	526,269	6,207,231	54,574	87,872,111
Petroleum refining products	2001	4,728,555	950,970,461	8,677	3,847,475
	2004	4,483,749	901,736,894	8,228	3,648,284
	2006	10,202,990	2,051,946,294	18,723	8,301,848
Primary iron and steel products	2001	339,857	3,287,583	1,538	800,035
	2004	822,616	7,957,531	3,723	1,936,469
	2006	948,547	9,175,710	4,293	2,232,914
Special-purpose machinery	2001	203,613	2,508,090	1,306	1,092,911
	2004	247,037	3,042,986	1,585	1,325,994
	2006	209,777	2,781,461	2,118	2,205,851
Sum of the above eight sectors	2001	134,154,736	2,217,240,747	158,945	61,407,317
	2004	152,602,392	2,357,872,659	201,997	91,908,426
	2006	189,524,411	3,877,393,339	296,946	163,491,779
Total	2001	136,328,805	2,254,819,512	172,339	71,381,440
	2004	155,784,775	2,411,703,723	221,641	106,458,155
	2006	202,056,338	4,070,223,053	364,778	188,612,232

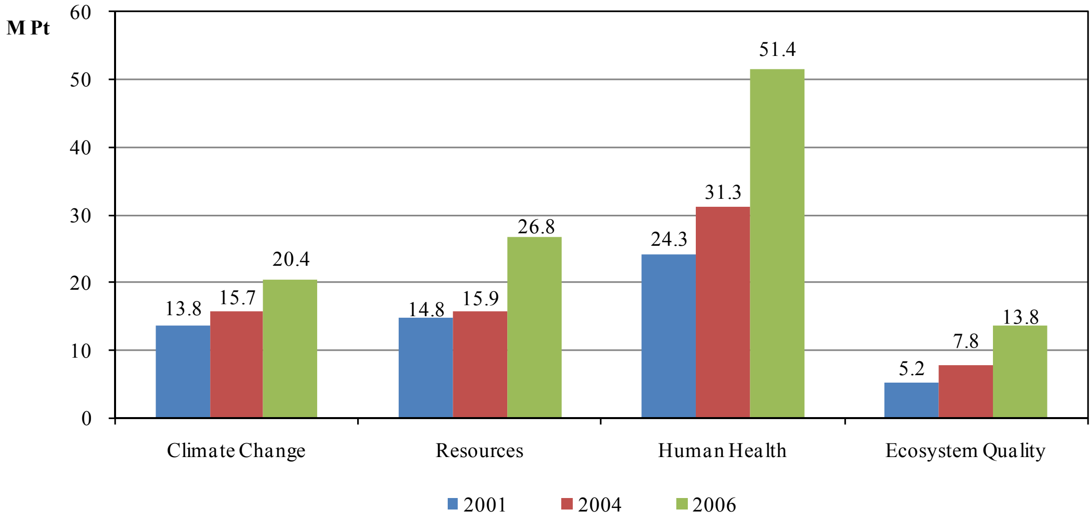

Fig. 1. Normalized environmental damages for 2001, 2004, 2006.

The amount of the resource use of the latter is 2,052 million GJ in 2006, and is higher than that of the former since 2006. For ecosystem quality category, the sector of other metals is the main contributor to influence the ecosystem quality, and its proportion has risen obviously from 30% in 2001 to 45% in 2006. The second largest is the electricity sector. However, its impact value increases slowly, and the proportion decreases from 35% in 2001 to 18% in 2006. The value of all kinds of environmental damages from the petroleum refining sector increased significantly from 2001 to 2006 (Table 3). This may result from the completion of phase four expansion of Formosa Petrochemical Corporation's No. 6 naphtha cracker project in Mailiao.

Fig. 1 shows that all damage categories are identical in rank among different years. "Human health" is the most significant environmental damage, followed by "resources", "climate change" and "ecosystem quality". In addition, all environmental damages increased continuously from 2001 to 2006, especially for the human health category. The damage value of human health increases more than one time, from 172,339 DALY in 2001 to 364,778 DALY in 2006. This increment is not attributed to the electricity sector, but mainly comes from two indirect sectors including the non-metallic minerals sector and other metals sector. In addition, arsenic and $PM_{2.5}$ are the main substances which increased indirectly more than 2.5 times from 2001 to 2006. It reveals that the authorities should pay more attention to reduce the electricity sector's direct and indirect emissions which endanger the human health. It is necessary to legislate against excess $PM_{2.5}$ emissions from manufacturing industries, and to consider implementing stricter arsenic emission standards to soil and water treatment.

Based on the above interpretation, we find that the direct environmental impact from production processes of the electricity sector is one of the main sources for each kind of environmental damage, especially for the climate change category. However, despite the continuous growth in damage value, the relative percentage of environmental impacts from the electricity sector decreased during 2001 to 2006. It may result from two reasons. First, the electricity sector has started to limit the emission of direct pollutants such as SO_2 and to economize the resource use and fuel consumption. It is moving toward cleaner production and sustainable development. Second, the amount of indirect emissions and consumptions from sectors on the supply chain increase more quickly than the direct ones from the electricity sector. The manufacturing industries should move towards low carbon fuel structure to reduce the CO_2 emission intensity.

It is worth to analyze the specific impact category of environmental damages and to observe the variation of the ratio of direct/indirect environmental impacts. The above results for damage level are the quantified representation of the environmental quality change. In practice, the damage level results are the simplified model of a complex reality, giving only a coarse approximation to the quality status of the item (Jolliet *et al*., 2003). For detailed description, LCA results on midpoint level are also presented successively.

Table 4 shows the environmental impacts on midpoint levels of the resource damage category. We find that the massive consumption of non-renewable energy is the leading proportion of resource consumption, especially for the fossil fuel combustion in the power generation process and the generation of petroleum refining products. In 2006, the sector of petroleum refining products becomes the largest portion of energy consumption and uses more than 2,000 million GJ energy to support the operation of the electricity sector. In addition, results for the mineral extraction category are identical with the real situation in Taiwan. Taiwan is one of the countries with limited self-producing energy resources and imports more than 98% of its fossil fuels such as coal, oil and natural gas.

For the climate change category in IMPACT 2002+ method, the damage of climate change to human health and ecosystem quality are not accurate enough to derive reliable damage factors. Therefore, the global warming is considered as a stand-alone midpoint level and damage level category.

Table 4. Environmental impacts on midpoint level of resource damage category.

Sector	Year	Non-renewable energy (GJ)	Mineral extraction (GJ)
Coal products	2001	33,744,380	172
	2004	40,005,130	203
	2006	66,485,221	338
Electricity	2001	1,163,304,866	11,385
	2004	1,308,801,402	12,809
	2006	1,555,267,129	15,222
Non-metallic minerals	2001	36,918,500	4,118
	2004	70,364,304	7,848
	2006	136,664,777	45,572
Other chemical materials	2001	24,886,923	1,863
	2004	22,666,918	1,696
	2006	48,800,732	3,652
Other metals	2001	1,598,776	3,631
	2004	3,267,516	7,421
	2006	6,193,165	14,066
Petroleum refining products	2001	950,967,211	3,250
	2004	901,733,813	3,082
	2006	2,051,939,281	7,013
Primary iron and steel products	2001	3,286,112	1,471
	2004	7,953,971	3,559
	2006	9,171,606	4,104
Special-purpose machinery	2001	2,507,233	857
	2004	3,041,947	1,040
	2006	2,780,482	978
Sum of the above eight sectors	2001	2,214,706,768	25,889
	2004	2,357,835,000	37,659
	2006	3,877,302,393	90,946
Total	2001	2,254,787,762	31,749
	2004	2,411,658,808	44,915
	2006	4,070,109,995	113,059

For the human health category in IMPACT 2002+ method, human toxicity (carcinogenic and non-carcinogenic effects), respiratory effects (inorganics and organics), and ozone layer depletion all contribute to human health damages (Jolliet *et al.*, 2003). All of these midpoint characterization categories in Table 5 are expressed in disability adjusted life years (DALY). Results in Table 5 show that more than half of human health damages are resulted from the inorganic respiratory effects. Emissions including sulfur dioxide, nitrogen dioxide, and particulates such as $PM_{2.5}$ and PM_{10} are the typical man-made pollutants generated from the production process of related industries, and can be inhaled deeply to the pulmonary alveolus, thereby causing serious damage to the respiratory systems with other adhered pollutants. This could reduce the average life-span of residents around the plants. Based on the report of Committee on the Medical Effects of Air Pollutants (COMEAP) in UK (COMEAP, 2009), a modest 10 microgramme/m^3 increase in the ambient annual average level of $PM_{2.5}$ is associated with a 6% increase in death rate. In addition, human health damages also result from carcinogenic and non-carcinogenic effects. Arsenic is one of the toxic metals in the coal and remains in the fly ash or bottom ash when the coal is burned. Arsenic could lead to cancers and nervous system disease. The cancer risk would be raised by a hundred times if the drinking water is contaminated by coal cinders (Yu *et al*., 2007).

The normalized environmental impact per midpoint level categories is presented in Fig. 2. The midpoint categories of aquatic acidification and aquatic eutrophication are excluded. It is because their damage units and normalization factors are under development (Jolliet *et al*., 2003). We find that five kinds of categories including global warming effects, non-renewable energy consumption, non-carcinogens effects, respiratory inorganics effects, and terrestrial ecotoxicity effects have higher impact value than others. This provides specific information to the authorities to deal with environmental pollutants at the same time.

According to the impacts from the electricity sector itself and other related sectors, the sum of the electricity sector's environmental impacts can be divided into direct and indirect impacts. The proportions of direct and indirect impacts on each environmental damage category are shown in Table 6. We can find that direct impacts take a huge proportion (92%, 91% and 83%) over the indirect impacts on the "climate change" category in 2001, 2004 and 2006. It reveals that power generation through fossil fuel combustion in thermal power plants is still the largest CO_2 emission

Table 5. Environmental impacts of human health damage category.

Sector	Year	Carcinogens (DALY)	Non-Carcinogens (DALY)	Respiratory inorganics (DALY)	Ozone layer depletion (DALY)	Respiratory organics (DALY)
Coal products	2001	15.33	129.01	752.78	3.53	0.83
	2004	18.17	152.95	892.45	4.18	0.98
	2006	30.20	254.19	1,483.17	6.95	1.63
Electricity	2001	1,823.44	11,551.33	88,649.79	17.83	27.91
	2004	2,051.50	12,996.08	99,737.37	20.06	31.40
	2006	2,437.83	15,443.42	118,519.32	23.84	37.31
Non-metallic minerals	2001	210.17	2,095.38	9,009.88	2.42	3.62
	2004	400.58	3,993.66	17,172.25	4.62	6.90
	2006	2,213.48	22,710.35	5,479.05	12.92	16.88
Other chemical materials	2001	182.48	1,748.33	567.52	9.33	3.54
	2004	166.20	1,592.38	516.90	8.49	3.23
	2006	357.82	3,428.31	1,112.86	18.29	6.95
Other metals	2001	627.31	6,549.52	228.64	0.59	0.45
	2004	1,282.08	13,385.64	467.28	1.20	0.92
	2006	2,430.02	25,370.81	885.66	2.27	1.75
Petroleum refining products	2001	215.81	2,002.31	4,375.64	6.80	11.27
	2004	204.63	1,898.64	4,149.11	6.45	10.69
	2006	465.65	4,320.45	9,441.49	14.68	24.32
Primary iron and steel products	2001	63.31	642.99	173.58	0.26	0.39
	2004	153.23	1,556.35	420.15	0.63	0.95
	2006	176.69	1,794.61	484.47	0.73	1.09
Special-purpose machinery	2001	54.47	542.90	151.91	0.43	0.41
	2004	66.09	658.69	184.30	0.52	0.50
	2006	88.97	911.35	185.53	0.65	0.60
Sum of the above eight sectors	2001	3,137.84	24,718.88	103,757.83	40.77	48.01
	2004	4,342.48	36,234.40	123,539.81	46.17	55.56
	2006	8,200.66	74,233.48	137,591.56	80.34	90.53
Total	2001	3,675.04	30,050.98	107,104.84	51.41	56.84
	2004	5,059.23	43,364.86	128,003.56	61.02	67.44
	2006	9,662.35	88,763.44	174,483.71	113.98	116.92

source, when considering any CO_2 emissions from the electricity sector and related sectors in the input/output supply chain.

In addition, the proportion on direct impacts of the “resources” category in 2001 and 2004 are more than 50%, but it drops to 38% in 2006. There is a similar condition to the direct impacts of the “human health” category, and the proportion varies from 66% in 2001 to 58% in 2004 and 42% in 2001. It shows that the indirect impacts of resources and human health categories could not be ignored, and become more significant year by year. The possible reason may be the extensive investment in and continuous development of related sectors such as the petroleum refining products sector. Finally, the proportions on direct impacts of the ”ecosystem quality” category are only 36%, 27% and 18% in 2001, 2004 and 2006. These proportions are clearly smaller than indirect ones. Traditional process-based LCA which only evaluates direct impacts from the electricity sector would underestimate more than half of total impacts.

Policy Implications

According to the 4th National Energy Conference in Taiwan (2009) and the newly-proposed Energy Management Act (2010), the government proposed the following energy policy goals. (Bureau of Energy, 2010).

1. **Upgrade energy efficiency in all sectors:** compared to the value of energy intensity in 2005, it should be reduced 20% by 2015; and energy intensity should be lowered 50% by 2025.
2. **Promote “clean energy”:** Renewable energy will occupy 8% of the total energy by 2025. Low-carbon fuel is aimed to reach 40 % of the total energy sources, with 50% of the total to be used in electricity-generating power plants. Natural gas should occupy 25% of the total energy by 2025 and CO_2 emissions should return to the 2005 levels by 2025.
3. **Supply sufficient energy:** Stabilize energy supply in order to satisfy continuous economic growth in the future. Markets with lower import costs and stable policies should be explored to ensure an adequate and continual energy supply at lower costs.
4. **Enhance energy-savings:** Promote a low-carbon society for the domestic and industrial sectors and stimulate the growth of green energy technology.

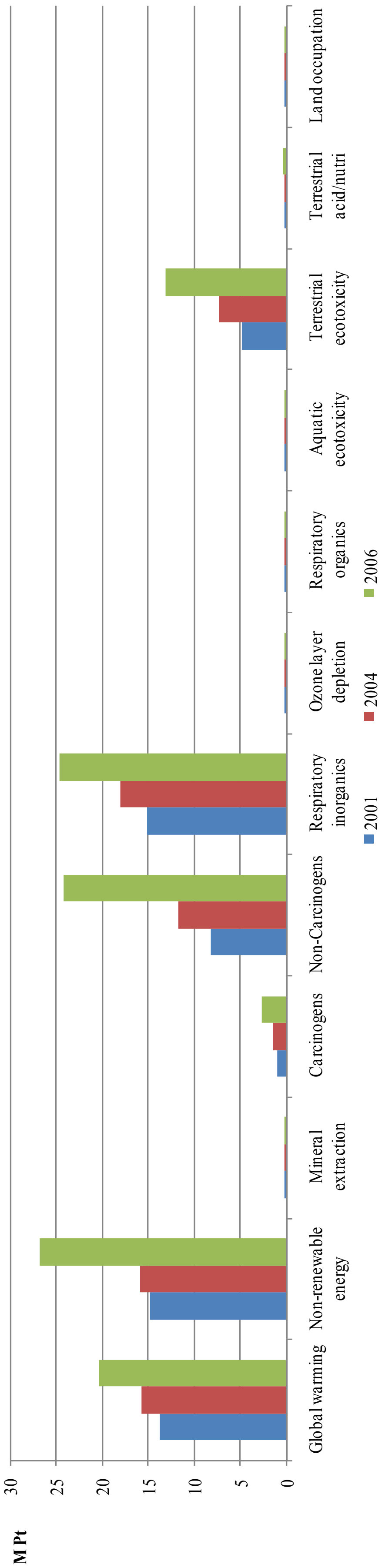

Fig. 2. Normalized environmental impacts for 2001, 2004, 2006.

Suggestions from our research for accomplishing some of the above proposed government policies and mitigating environmental impacts are as follows: (1) To upgrade energy efficiency, old fossil power plants and other such facilities should be phased out as soon as possible and replaced with BACT (best advancement control technology) facilities. For example, IGCC and CHP plants could increase their efficiency and reduce their pollution significantly. (2) The fossil fuel plants in Taiwan occupy more than 75% of the present energy-related power, and they will continue to play a significant role in the future; therefore, international cooperation for clean-coal technology and carbon sequestration are needed to lower the CO_2 and other emissions that characterize the fossil fuel industry. (3) The government must continue to search for those international markets that provide better fuel quality and stable supply in order to minimize maintenance and maximize the security of imported energy supplies. Because Taiwan has already declared a "no-nuke" policy (moratorium) on additional new nuclear power plants after the current one (4^{th}) is completed, the country must make up part of the future loss of electricity power caused by reduction of the nuclear power percentage by implementing alternative energy sources such as renewable energy, solar and wind power. Furthermore, the March 11, 2011, Fukushima earthquake near Japan and its related nuclear power plant problems have focused Taiwan's public attention on the safety standards of its existing plants, with a primary focus on how to calm the public's fears about nuclear mishaps. The three existing nuclear power plants are reaching their 30-year limits, and whether or not their lifespan will be extended has become a hot topic of debate. This issue must be resolved before additional specific policies can be formulated for this power source. (4) Demand-side management should be strengthened by all energy-related sectors so as to cut consumer demand and thereby save more energy. Furthermore, the transportation, residential and commercial sectors must promote the following programs: efficient public transportation, green buildings and energy-saving facilities, upgrade of basic equipment and infrastructure. For example, according to current practice in Taiwan, if a household saves electricity each month, its electricity bill will be reduced proportionally. (5) Higher standards and effective incentives need to be enhanced in order to promote more energy-savings in industry. The government must require high energy intensity industries such as IC, petroleum, steel, etc. to meet stricter standards and to upgrade their energy efficiencies; these industries must also develop voluntary initiatives for energy savings and CO_2 reduction. (6) Besides the electricity industry itself, the indirect impacts identified by this research suggest that the other sectors, such as "non-metallic minerals" and "other metals", are the major sources of human health damage; therefore, stricter regulatory standards must be implemented. (7) Regarding resource damages, the major non-electricity source is "petroleum refining products". Restructuring and down-sizing of this sector should be considered for future action. (8) The top source for impact of climate change is "electricity", followed by "petroleum-refining products",

Table 6. Proportions of direct/indirect environmental impacts.

		Climate Change	Resources	Human Health	Ecosystem Quality
2001	Direct	92%	52%	66%	36%
	Indirect	8%	48%	34%	64%
2004	Direct	91%	54%	58%	27%
	Indirect	9%	46%	42%	73%
2006	Direct	83%	38%	42%	18%
	Indirect	17%	62%	58%	82%

and "non-metallic minerals". It is anticipated that industry-restructuring will lower energy consumption and will increase value-added products. Also, lower-carbon fuels and demand-side management for these three sources is urgently needed. Old fossil power plants and facilities should be phased out as soon as possible and replaced with BACT facilities. (9) Ecosystem damage is largely-sourced from the "electricity" and "other metals" sectors. Effluent standards and ecosystem safeguards should be stricter because of their significant environmental impacts. Technology of the upstream polluting industries must be advanced toward greener technology and "eco-friendly" outputs; otherwise, they may lose their competitiveness and suffer the fate of down sizing in the future.

CONCLUSIONS

In this paper, we used IO-LCA to analyze the direct and indirect environmental impacts of Taiwan's electricity sector. The SimaPro 7 program (IMPACT 2002+) was employed to evaluate the impact value for four damage categories and several midpoint level categories. Results from damage assessment are important for the allocation of resources in a country regarding human health, the ecosystem and resource consumption. For Taiwan's electricity sector, "human health" is the most significant environmental damage in 2001, 2004 and 2006, followed by "resources", "climate change" and "ecosystem quality". In addition, all damages have continuously increased, especially for the "human health" category. Urgent legislation is necessary for damages to human health caused by excess environmental pollutants such as $PM_{2.5}$ and arsenic.

Moreover, our results also show that "global warming effects", "non-renewable energy consumption", "non-carcinogens effects", "respiratory inorganics effects", and "terrestrial ecotoxicity effects" are significant midpoint level impact categories. The massive CO_2 emissions from power generation processes have direct impacts on climate change. However, the proportions of indirect impacts are increasing gradually from 8% in 2001 to 17% in 2006 to the point where there would be a huge underestimation of impact values if the related sectors in the input/output table are omitted from the calculations. Findings of this study are beneficial for improving the environment and for related policy-makings involving the electricity sector in Taiwan.

According to the results in this study, Taiwan's government needs to set up a series of stricter emission standards and operation procedures to lower the direct environmental impacts. For example, the authorities could establish energy-saving expert groups to develop a control mechanism for saving electricity. Voluntary emission reduction programs are recommended to reduce air pollutants as well as CO_2 emissions. The electricity sector should not only adjust the energy supply structure, but also increase the proportion of green energy including hydro-power, wind-power and renewable energy to reduce the fossil fuel-fired generators in Taiwan. Otherwise, the power plants could replace old generators with new ones to promote productive efficiency. On the other hand, the authorities could reduce the electricity lost by improving the electrical power transmission and distribution.

Moreover, we propose stricter regulations of the related suppliers and consumers to reduce the indirect impacts of the electricity sector. Suppliers with the best available technology (BAT) and least resource consumption and lowest environmental impacts could be given incentives or rewards for their success. In addition, the Taiwan government should keep promoting the legislation and revision of "Energy Management Act" and "GHG Reduction Law". The establishment of GHG inventory and trading systems and the total mass control of emissions are also urgently required. Considering demand side management (DSM), we could promote energy-saving to raise the efficiency of electricity consumption by the residential and commercial sectors. Finally, the methodology used in this research can be applied to other vital sectors of the economy to evaluate their environmental impacts.

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