REVIEW ARTICLE

The PCA and IOA approaches for life-cycle analysis of greenhouse gas emissions from Thai commodities and energy consumption

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Abstract

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The use of more substitutable commodities, selected by their total greenhouse gas (GHG) emissions would highly contribute to mitigating the effects of global warming. Life-cycle analysis (LCA) is a solution that can evaluate the total emissions from a lifetime production of a commodity. It is widely applied to reveal the actual environmental emissions in many countries, however this data could not be applied in other countries due to different emission and energy consumption structures. LCA emission factors within the same country are also different due to different assumptions on the boundary and lifetime of a considered production process. The process chains analysis (PCA), the conventional LCA approach which is mostly applied in Thailand, is accurate in the direct production process, but its analysis in the higher order production process is usually truncated due to a lack of data. It is laborious, time consuming, and hard to gather all the data from the whole production process. This article presents the pros and cons of PCA and input-output analysis (IOA) and introduces an appropriate approach in a Thai context. The adaptation of energy-related GHG emissions findings in the revised 1996 Intergovernmental Panel on Climate Change (IPCC) guidelines for national GHG inventories are introduced for a commodity emission factor and traced through

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the whole production chains by IOA. In conclusion, the IOA gives emissions in average values and the historical economic structure is used to derive the emissions. However, emissions from every single link of production lifecycle can be taken into account. A combined PCA and IOA is recommended for an LCA of GHG emissions in Thailand.

Key words : life-cycle analysis, greenhouse gas emission factor, energy intensity, process chain analysis, input-output analysis

บทคัดย่อ

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วิธี PCA และ IOA สำหรับการประเมินปริมาณการใช้พลังงานและการปลดปล่อยแก๊สเรือนกระจกจากการผลิตผลิตภัณฑ์ในประเทศไทยโดยการวิเคราะห์วัฏจักรชีวิต

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การพิจารณาถึงปริมาณการปลดปล่อยแก๊สเรือนกระจกในการเลือกใช้ผลิตภัณฑ์ใดจากจำนวนผลิตภัณฑ์ที่สามารถทดแทนกันได้นั้นจะมีส่วนอย่างมากในการช่วยบรรเทาปัญหาโลกร้อนจากสภาวะเรือนกระจก วิธีการหนึ่งที่ใช้ในการประเมินปริมาณแก๊สเรือนกระจกทั้งหมดที่ปลดปล่อยออกมาตลอดชั่วอายุของการผลิตผลิตภัณฑ์หนึ่ง ๆ คือ การวิเคราะห์วัฏจักรชีวิตของผลิตภัณฑ์ (LCA) ซึ่งเป็นที่นิยมกันในประเทศพัฒนาแล้วหลาย ๆ ประเทศเพื่อใช้ในการวิเคราะห์ปริมาณมลภาวะที่แท้จริงที่ปลดปล่อยสู่สิ่งแวดล้อม เนื่องจากความแตกต่างด้านโครงสร้างการใช้พลังงานและโครงสร้างของปริมาณแก๊สที่ปลดปล่อยออกมาในแต่ละประเทศทำให้เราไม่สามารถนำข้อมูลการศึกษาจากประเทศหนึ่ง ๆ มาศึกษากับอีกประเทศหนึ่งได้ นอกจากนี้ข้อมูลการศึกษาของผลิตภัณฑ์ในประเทศเดียวกันก็อาจจะไม่ตรงกันเนื่องจากการใช้สมมติฐานกำหนดขอบเขตการวิเคราะห์และกำหนดอายุผลิตภัณฑ์ไม่เท่ากัน วิธีการวิเคราะห์วัฏจักรชีวิตของผลิตภัณฑ์ มีวิธีหลักอยู่ 2 วิธีคือ process chains analysis (PCA) และ input-output analysis (IOA) วิธี PCA เป็นวิธีเดิมที่นิยมใช้ในประเทศไทย ซึ่งเป็นวิธีที่ให้ผลที่แม่นยำในกระบวนการผลิตโดยตรง แต่ข้อมูลในกระบวนการผลิตทางอ้อมมักจะถูกตัดออกเนื่องจากไม่สามารถหามาวิเคราะห์ได้ วิธีการนี้เป็นวิธีการที่ต้องใช้เวลาและความพยายามในการเก็บข้อมูลสูงมาก และไม่สามารถจะรวมข้อมูลในกระบวนการผลิตทางอ้อมได้ทั้งหมด บทความนี้ได้แสดงถึงข้อดีและข้อเสียของทั้ง 2 วิธีการดังกล่าว และเสนอแนวทางในการวิเคราะห์ที่ใช้เวลาน้อยลงสำหรับการวิจัยด้านนี้ในประเทศไทย โดยการนำค่าสัมประสิทธิ์การปลดปล่อยแก๊สเรือนกระจกที่ Intergovernmental Panel on Climate Change (IPCC) แนะนำให้ใช้ในการประเมินปริมาณแก๊สเรือนกระจกในระดับประเทศ มาประเมินค่าปริมาณการปลดปล่อยแก๊สเรือนกระจกจากผลิตภัณฑ์หนึ่ง ๆ วิเคราะห์กระบวนการผลิตทางตรงโดยวิธี PCA และวิเคราะห์ปริมาณการปลดปล่อยแก๊สจากกระบวนการผลิตทางอ้อมทั้งหมดด้วยวิธี IOA โดยสรุปวิธี IOA มีข้อเสียคือความแม่นยำของการประมาณค่าปริมาณแก๊สเป็นค่าเฉลี่ยจากภาคเศรษฐกิจหนึ่ง ๆ ซึ่งอาจจะผลิตสินค้าหลายอย่างในหมวดเดียวกัน แต่ก็สามารถรวบรวมปริมาณแก๊สที่ปลดปล่อยจากกระบวนการผลิตทางอ้อมได้ครบถ้วนทั้งหมด ดังนั้นจึงแนะนำให้ใช้วิธีการประสมระหว่าง PCA และ IOA ในการประเมินการปลดปล่อยแก๊สเรือนกระจกโดยวิธีการวิเคราะห์วัฏจักรชีวิตของผลิตภัณฑ์ (LCA) สำหรับกรณีศึกษาในประเทศไทย

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Consuming low emission commodities could successfully contribute to the global warming mitigation action, but only its estimation of direct emissions from a considered system might mislead the policy action. The LCA is an increasingly important tool used to compare the environmental impacts of substitutable products (Hondo *et al.*, 2002). The LCA of an energy system originated from the net energy analysis that has been widely applied since 1980s is usually called full-energy-chain analysis. All flows of GHG-intensive energy and materials associated with the life cycle are important in accounting the total emissions of GHGs from the completed chain of energy consumption within a system (Van de Vate, 1994a).

LCA is currently studied in order to reveal the actual environmental emissions from a final consumption in many developed countries. Limited LCA have been studied in Thailand, and most of them are analyzed by PCA. Emission factors from LCA are site specific, so the data from one country can not be applied to another due to different energy and emission endowments. The sources of uncertainty in emissions estimated from LCA are summarized by Van de Vate (1997) including

a) Different analytical methods

b) Different Input database

c) Outdated economic database, particularly in the IOA approach

d) The use of global warming potential (GWP), particularly of methane (CH4)

e) Lifetimes of the devices

f) Different assumptions of system boundaries

g) The site-specific nature of the energy chains or parts of them due to the national variability of technologies, industries, energy endowment etc.

GHG emissions from electricity used in manufacturing a commodity depend on the national fuel mix for power generation. An important factor is the electricity mix that varies from country to country (Voorspools *et al.*, 2000). Though the universal emission factor for electricity generation does not exist, applicable emission factors of developed countries, west european grid, and developing countries may be applied (Van de Vate, 1997). GHG emission factors from various countries are presented in Table 1.

The major sources of difference in emission factors are different system boundaries and different analytical methods (Van de Vate, 1997). Two basic approaches are available for energy chain analysis, namely process chain analysis (PCA) and input-output analysis (IOA) (Van de Vate, 1997). Derivation of energy and emission by IOA is based on cost basis, whereas the derivation by PCA is based on the mass of the material. Either PCA or IOA has their individual advantages and disadvantages. This article aims at reviewing available approaches for the evaluation of life cycle energy-related GHG emissions from a commodity, and to introduce a short-term approach to fill the gap of none available data for LCA.

Process Chains Analysis (PCA)

PCA basis is an inventory analysis using bottom-up data collection. It investigates the flow of materials and energy in each production process.

Table 1. GHG emission factors of electricity generation from various countries

Country	GHG emission factor (g $CO_{2\,eqv}$/kWh)
Developed countries[1]	500
West European[1]	520
Developing countries[1]	735-740
Belgium[2]	340
France[2]	120
Germany[2]	720

Note: [1]data from Van de Vate (1997)
[2]data from Voorspools *et al.* (2000)

Each material or energy that forms the main process is traced back through its initial extraction. It evaluates the embedded energy and the embedded emissions caused by the material production (Voorspools *et al.*, 2000). PCA considers all individual emission points of GHG, and therefore requires careful analysis of all flow of energy and materials associated with its links of production processes. Hence, emission factors of all energy types and all materials required by all the process steps must be available.

Figure 1 is an example of an electricity production chain. It presents the links of higher order subprocesses that the main production process of a particular commodity requires. Conventional GHGs estimation concerns only emissions from the energy conversion stage of the main process. The main process directly generates emissions and consumes energy but it needs various inputs. The upstream production processes of these inputs also generate emissions and consume energy. Emissions from the main process are defined as direct emissions. Emissions from the higher order subprocesses are indirect emissions. Indirect emissions could occur from either fuel chain (i.e. conversion, production, distribution and transportation), or production chains of materials and services supplied (i.e. construction, operation and maintenance stages). Full energy chains analysis reveal that the absence of direct emissions does not mean that the product is emission-free. Non-fossil electric generators, such as hydropower, wind, and nuclear power generation, cannot produce electricity without releasing GHGs from the links of the whole energy chain (Van de Vate, 1997) (Gagnon and Van de Vate, 1997) (Schleisner, 2000).

In 1993, PCA was adopted into the official guidelines for LCA and set out by the Society of Environmental Toxicology And Chemistry (SETAC) (Fava *et al.*, 1993). LCA of energy systems is applied in ExternE project of the European Commission (ETSU, 1995) (Schleisner, 2000), the project on databases and methodologies for assessment of different energy sources for electricity generation (DECADES) of the International Atomic Energy Agency (Vladu, 1996), the Global Emission Model for Integrated Systems (GEMIS) project of the Oko-Institut (GEMIS, 2003) and the Gesamthochschule Kassel, or the Swiss GaBE project (Lenzen and Munksgaard,

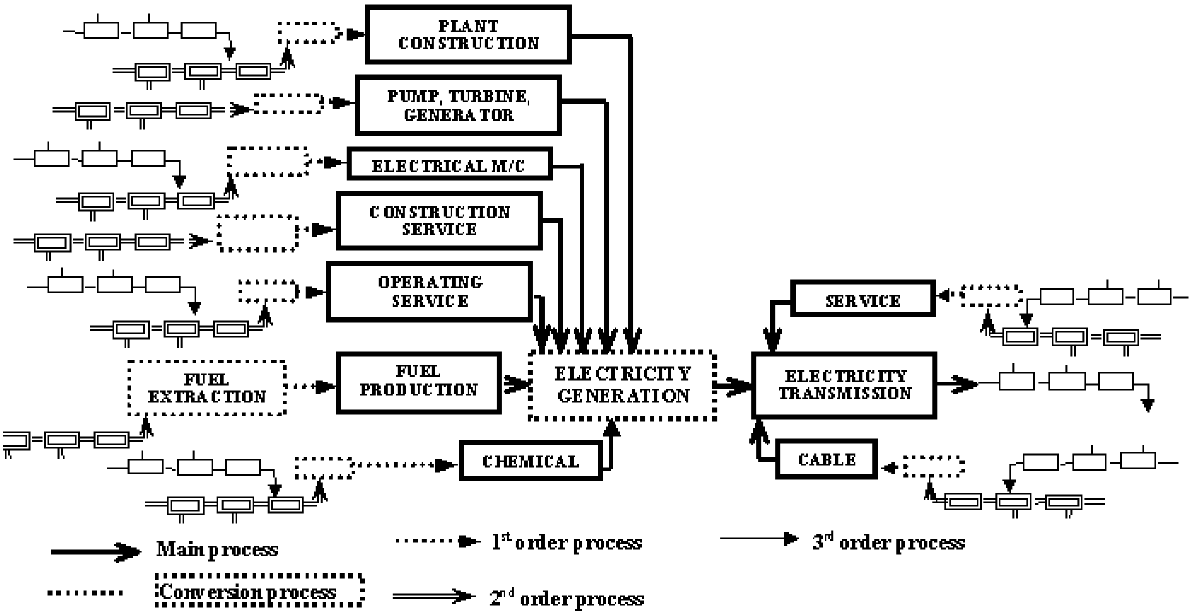

Figure 1. Production chains of electricity generation.

2002). In 1997 the LCA principle was developed as the ISO14040 standard for investigating environmental loads (ISO, 1997a) (ISO, 1997b) (ISO, 1997c) (ISO, 1997d). An application of ISO 14040 to compare among selected bioenergy transport chains was performed by Forsberge (2000).

PCA takes advantage by giving information on the minor details that have a large impact and on the important aspects of the real systems, these results could reflect the realities and demands knowledge of the specific systems (Miljϕstyrelsen, 2001). However, the application of PCA is hardly applied to Thailand in a short-term period because of limited local LCA research and laborious data collection. PCA needs to gather details by auditing (Lenzen and Munksgaard, 2002), hence, data availability is the major problem. For example, an application of LCA by PCA in the DECADES project could not be fulfilled due to the lack of front end and back end data (Limmeechokchai and Chungpaibulpatana, 1999). Sawatani Tadashi explained in a special workshop of "Life cycle inventory&life cycle assessment and case studies" on March 5, 2003 (conducted by the National Metal and Material Technology Center of Thailand) that the result from LCA is largely dependent on data availability and the justification of the researcher. Hence, by using the LCA result of a particular product, it is necessary to define the boundary and the method used.

Major errors from PCA are truncation errors, errors from non-physical amounts that could not be valued, and errors from an average factor. Some assumptions have to be made in PCA concerning the country of origin of the materials, and their manufacturing processes, disposal and recycling processes (Schleisner, 2000). Boundary truncation is a major problem due to the non-availability of process data in higher orders of the subprocess chains (Lenzen and Dey, 2000). The higher subprocess orders that data cannot be explored are definitely truncated somewhere within the upstream link (Friedrich and Marheineke, 1994) (Lenzen and Dey, 2000). Dealing with the completed energy chain implies that upstream or downstream parts of the energy chains are often outside the national borders (Van de Vate, 1994b). Assumptions concerning the country of origin of the materials, their manufacturing processes, disposal and recycling processes are needed (Schleisner, 2000). Some truncation errors might come from cases where processes cannot be expressed in the material used (e.g. engineering, construction, services, etc.) and then they are overlooked in the analysis (Lenzen and Trelor, 2002). Using the case of a steel industry in a full energy chain analysis, Lenzen and Dey (2000) points out that up to 50% of the environmental exchanges related to a product can be left out according to the process analysis. However, the range of the error from PCA depends on the significance of upstream chain of each subprocess. Other errors are caused by using the average factors of either low or high-energy consumed materials made from the same basic material. Energy and emissions embedded in imported commodities could not be easily considered in PCA due to the data requirements of higher subprocess chain.

It is impossible for PCA to cover the whole process of a life cycle of any particular product. A possibility could be to fill out data gaps with information from the IOA (Milj(styrelsen, 2001). The IOA takes advantage of capturing all propagation of energy and GHGs from production chains up to infinite orders, provide sufficient results for comparison among commodities, and is time and cost efficient for data gathering and for completing calculation tasks (Lenzen, 2002).

Input-Output Analysis (IOA)

An I-O table describes the flow of goods and services between all individual sectors of a national economy over a given period. The interrelationship between economic sectors is shown in Figure 2. The IOA, a top-down economic technique, firstly was applied by Loentief (1986). It divides a product into the components that are supplied by various industries. An economic sector is a representative of a group of industries producing the same product. For each sector, an average product is characterized by evaluating the amount of energy needed and the amount of GHGs emitted (Voorspools *et al*., 2000). To trace the resource

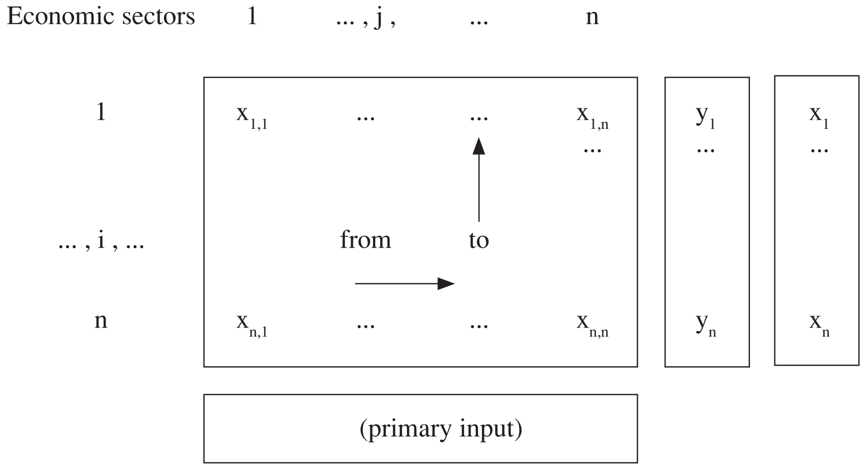

Figure 2. A simple input-output table

requirements and the pollutants released throughout the whole economy, sectoral monetary transaction matrices are used to describe the complex interdependencies of industries (Miljϕstyrelsen, 2001).

Since 1960s IOA has been applied extensively to an environmental analysis (Lenzen and Trelor, 2002). Wright (1975) used the IOA technique to derive energy intensity, but addressed "energy cost" of goods and services in the USA in 1963. Thereafter, Bullard and Herendeen (1975) derived the energy costs among the US economy in 1967. Hannon *et al.* (1983) made a comparison of primary energy intensity in the USA in 1963, 1967, and 1972. Since 1994, it has been widely used for energy chain analysis for comparative assessment of GHG emissions by IAEA.

IOA is an optional approach that aims at solving the truncation and time-consuming problems of PCA. It takes advantage of capturing all propagation of energy and GHGs from production chains up to infinite orders, by providing sufficient results for the comparison among commodities, and reducing time. It is cost effective for data gathering and calculation tasks (Lenzen, 2002). The input-output (I-O) table of a national economy describes the entire production of the branches and their interdependencies (Friedrich and Marheineke, 1994). The material inputs associated with the specific sectors of an entire economy are identified (Norton *et al.*, 1998). National economic sector/commodity statistics are used to derive the energy flow into emissions from the various links of the full-energy-chains analysis (Van de Vate, 1997). Non-material inputs can also be taken into account (Voorspools *et al.*, 2000) (Lenzen and Trelor, 2002).

Van de Vate (1994b) pointed out that the present approach of the IPCC Guidelines for National Inventories of GHG emissions did not include national energy consumption related "imported" or "exported" GHG emissions from outside national borders. It is possible to evaluate the emissions attributable to transactions outside national borders in IOA (Lenzen, 2001). Wright (1975) found significantly different figures in energy intensities of US commodities and suggested not neglecting the imports, particularly in a study of individual commodities. Schaeffer and Leal de Sa (1996) found that the amount of energy and carbon embodied in the non-energy exports and imports of Brazil is significant.

IOA can be used as a tool for the explanation of the interrelationship between economic activities and environmental emissions. It is a method of systematically quantifying the mutual interrelationships among the various sectors of a complex economic system (Loentief, 1986). The structure of each sector's production process is represented by a vector of structural coefficients that describes in quantitative terms the relationship between the inputs it absorbs and the output it produces. The interdependence among the sectors of a given economy is described by a set of linear equations. They express the balance between the total input and the aggregated output of each commodity or service that is produced and used in one or several periods. It is assumed that the inputs required by any sector are constant returns-to-scale, and there is no substitutability between inputs. The technical structure of the entire system can accordingly be represented concisely by a matrix of technical I-O coefficients of all its sectors.

The usual source of data is a system of national accounts that are often routinely collected by a means of census. Hence, providing an I-O table is often a prohibitively expensive and time-consuming endeavor. The Thai I-O table is normally provided by the National Economic and Social Development Board (NESDB, 2001) every 5 years. From Figure 2, a mathematical expression of total output from a sector is an aggregation of final demand and the intermediate demands.

$$x_i = y_i + \sum_{j=1}^{n} x_{i,j}$$

where $x_{i,j}$ = intermediate demand, y_i = final demand (private consumption + public consumption, investment, export), and x_i = total output.

Technological coefficients are derived from the original I-O table by dividing each element of the intermediate demand by the total production.

$$a_{ij} = x_{ij} / X_j$$

where a_{ij} is the technological coefficient for the i^{th} product as input factor to the j^{th} sector, x_{ij} is the demand for the i^{th} product by the j^{th} sector and X_j is the total production of the j^{th} sector.

Changing the final demand of a sector also causes indirect changes to all sectors, since the product of one sector is usually an input to others. The total impacts of the change are expressed in matrix operation;

$$X = [I - A]^{-1} Y$$

where X is the vector of total production, I is the unity matrix, A is the technological matrix. The matrix $[I\text{-}A]^{-1}$ is called the Loentief's coefficient, and represents the propagation of intermediate demand. It is called the induce coefficient and causes the "indirect" amount embedded in the total output. The term A·X could be explained as an aggregation of various indirect inputs for amount of production of X, while the term Y is the final demand, the final consumption, for the production of X.

The given element in the Loentief's coefficient depicts how much the output x_i of the i^{th} sector would increase if y_i, the quantity of good j absorbed by final user, has been increased by one unit. It explains a full- propagation chain of total monetary input needed from sector i for producing one monetary unit of output of sector j since $[I\text{-}A]^{-1} = [I]+[A]+[A]^2+[A]^3+...+[A]^p+...$ Which implies the way that IOA covers the requirements of the infinite order. While [I] coefficient is the direct input supplied to each sector, [A] represents the first-order chain of input, $[A]^2$ represents the second-order chain, ..., $[A]^p$ represents the p^{th} order, and [A] represents the infinite order.

However, major errors caused from IOA characteristics are the average value (no disparity between different products) of economic sectors, sectors disaggregation, and a projection of historic data (I-O table) on the present data (Voorspools *et al.*, 2000) (Hondo *et al.*, 2002). Norton *et al.* (1998) commented that the approach of an IOA is effective where over the industrial sector under consideration is a significant and identifiable component of the economy, and it is inappropriate for newly commercial technologies where components arise from many countries. Lenzen suggested reducing this error by incorporating IOA into the PCA (Lenzen, 2001). A combined PCA and IOA is proposed to minimize individual errors either completeness from PCA or detail errors from IOA (Miljϕstyrelsen, 2001).

The disaggregation errors are caused by grouping activities into a limited number of sectors, which might be difficult to use for detailed LCA purposes, except for homogeneous sectors

(Miljφstyrelsen, 2001). The number of sectors ranges from below 100 in Germany to around 800 in Japan (Miljφstyrelsen, 2001). Since I-O tables are not normally designed with the main purpose of exploring energy-environmental questions and they often aggregate the important energy sectors, Hawdon and Pearson (1995) decided to disaggregate the energy sector into 5 sectors. Wu and Chen (1989) disaggregated the energy-related sector into 99 sectors and finally re-aggregated it into 39 sectors. Many IOAs have to use a limited number of I-O sector in order to match the energy data. Hannon *et al.* (1983) aggregated 357 to 88 sectors for a matching purpose. Gay and Proops (1993) aggregated a 38-sector version of the 1984 I-O table. Hawdon and Pearson (1995) studied the energy-environment-economy interaction with an ENDAM program where only 10 sectors can be applied. Thai I-O table is available in 26, 58, and 180 sectors (NESDB, 2001). A summary of I-O sectors, the I-O year and the year of the paper issuing are listed and cited in Table 2.

The advantage of using an I-O model is that direct and indirect environment repercussions on different patterns of final demand can be explored (Hawdon and Pearson, 1995). Direct plus indirect emission coefficients indicate how much of each pollutant is emitted directly and indirectly in all sectors, per unit of final demand in each sector. Victor (1972) found an 8% fall in ecologic costs after number of the private car used in Canada was reduced by 50% and replaced by public transport.

IOA takes advantage of this policy's implication. Trends of energy intensity were studied for Taiwan by Wu and Chen (1989) and for Holland by Wiltling *et al.* (1998). Using a requirement matrix derived in monetary terms, Common and Salma (1992) carried out IOA accounting for changes in Australian CO_2 emissions over 1973/1974 to 1988/1989. Gay and Proops (1993) investigated the change of the UK economic structural by increasing the CO_2 concentration in atmosphere

Table 2. Number of sectors applied by IOA researchers

country	I-O year	Number of sectors	references
USA	1963	363	Wright (1974)
USA	1967	na.	Bullard and Herendeen (1975)
USA	1967	90	Costanza (1980)
UK	1974	102 (4 fuels)	Common and McPearson (1982)
USA	1963, 1967, 1972	aggregated 357 to 88	Hannon *et al.* (1983)
USA	1985	33	Wychoff and Roop (1994)
Canada	1986	33	Wychoff and Roop (1994)
UK	1984	27	Wychoff and Roop (1994)
Japan	1985	27	Wychoff and Roop (1994)
France	1985	24	Wychoff and Roop (1994)
Germany	1986	20	Wychoff and Roop (1994)
Taiwan	1976, 1981, 1984, 1986	99	Chen and Wu (1994)
Australia	1994/1995	aggregated from 108/28 to 27 (due to energy data on 27 sectors)	Common and Salma (1992)
UK	1984	38	Gay and Proops (1993)
UK	Na.	10	Hawdon and Pearson (1995)
UK	1984	101	Heterington (1996)
Greece	1988	123	Caloghirou *et al.* (1996)
Netherlands		56	Wiltling *et al.* (1998)
Australia	1992-1993	45	Lenzen (1998)
Spain	1992	na.	Labandeira and Labeaga (2002)
India	1983-84, 1989-90, 1993-94	115	Pachauri and Sprang (2002)

by IOA. They also recommended the using of IOA to explore the effect of varying the balance between fossil fuel and other forms of electricity generation, and of changing the composition of the final demand for goods and services. Ziegelmann *et al.* (2000) examined the net employment effects of an extension of renewable energy systems in Germany by using IOA technique.

The Thai 1998 I-O table is the most recent one (NESDB, 2001). Sector disaggregation is provided in much of the 180 sectors. All possible energy sectors are provided separately from other sectors. Moreover, a Thai IOA study takes advantage that the energy data is already matched with the I-O data. Hence, the sector aggregation error is not large. GHG emissions from energy activities in these 180 sectors could be examined by adapting the revised 1996 IPCC guideline for national GHG inventories. GHG emission factors embedded in the infinite propagation of production processes of materials and services are then determined by the IOA.

Combined Input-Output and Process Analysis

The combined input-output and process analysis is an alternative that provides the most accurate environmental impacts embodied within a system. Friedrich and Marheineke (1994) and Norton *et al.* (1998) also recommended using the combination of PCA and IOA to eliminate any disadvantage of using an individual PCA or IOA. However, the methods of combination are not consistent. Uchiyama (1996) developed a combination of the process analysis and the Japanese input-output table of LCA in order to evaluate the net energy requirements and the GHG emissions for the total electricity supply system from upstream links and downstream link.

The combined IOA & PCA is applied to achieve system completeness and to lessen the problem of selecting a boundary for the system (Lenzen and Munksgaard, 2002). Herendeen, Hannon and others at the Center of Advanced Computation in Urbana, Illinois, suggested to employ an IOA in order to account for the energy requirement originating from inputs out of upstream supply chains of infinite orders (Lenzen and Munkgaard, 2002). Since the IOA approach suffers from shortcomings such as aggregation and allocation errors, Bullard *et al.* (1978) developed a more complete and specific method that combines the advantages of either PCA or IOA.

In the review of the energy and CO_2 life-cycle analysis of wind turbines, Lenzen and Munksgard (2002) found large stochastic uncertainties pertaining to the relative energy contents of components of wind turbine systems. Beyond the stochastic uncertainties, process analyses carry truncation errors, which are caused by setting a finite system boundary. The review of Lenzen and Munksgaard (2002), Voorspools *et al.* (2000), and Hartmann (1996) found that energy or GHG intensities based on a material breakdown in weight units yielded energy intensities that were lower than the intensities based on cost breakdowns and input-output multipliers (IAEA, 1996). Lenzen (1999) also found truncation errors in solar thermal power plants, and Lenzen and Dey (2000) found an error of 50% in a PCA of energy content in basic iron and steel products.

Generally, in a combined IOA and PCA, after all processes have been described, energy and the materials requirements are calculated in the process analysis for all stages of plant construction, operation and maintenance (O&M), and dismantling of each process. The energy consumption of material production is calculated with the national Input-output table. Thereafter, the total life cycle input energy is summed up. The total energy of an electricity supply system is the total amount of electricity supplied to consumers during the plant life (Uchiyama, 1996). The problem with this combined approach is double counting from the main process and IOA. Using the 1988 I-O table, Friedrich and Marheineke (1994) evaluated life-cycle GHG emissions from electrical systems in Germany by combining input-output and process analysis. They also introduced additional decoupling of a process chain to avoid double counting.

Discussions on application of LCA in Thailand

LCA of GHG emissions are scattered due to deviations in approach, scope of system boundary, number of GHGs included, emission-activity sources, data availability, GWP, and the outdated or disaggregated I-O table. Most of the LCA attend on the link onto the system lifetime and perform the PCA approach. Different assumptions about the system boundary are the major source of deviation of results if PCA is applied. Consequently, sub-process links could not be extended to all of the actual links i.e. to infinite orders since it requires tedious field auditing. In some energy LCA, attention is only paid to the full links of fuel production, however, the links of material or service composed in the system's lifecycle are often stepped over. To express the actual total amount of GHG emitted by a product, it is necessary to cope with all dimensions of emission links. The emissions directly incurred from the system's lifecycle and indirectly embedded in the whole chain of the energy transformation from cradle to grave, and in the production chain of energy, materials and services should be included. The LCA should be performed by the PCA so that the life-cycle boundary is optional and circumscribed as far as the lifetime is defined or as far as data is available. Higher orders of production chains and energy chains are possibly enhanced by IOA technique and the rest of the subprocess boundary can be considered. The contribution of embedded emissions in import commodities is also significant to the emission factors.

GHGs other than CO_2 (i.e. CH_4, N_2O, etc.) should also be taken into account in order to express the actual global warming contribution. In addition, some other emission activities such as fugitive emissions or emissions from industrial process should be considered. Unfortunately, the country-specific database for GHG emissions in Thailand is not available. The generic data from IPCC, a reliable reference, is used whenever the country-specific value is not available. Currently, an international agreement on the IPCC's GWP is applied, hence the different use of global warming potential (GWP) is not a problem for GHG emission factors.

The method for LCA in a particular country depends on the nature and availability of the data. Since the database for PCA is not available in Thailand, deriving an emission factor from PCA requires not only the extensive tasks of energy, materials, and services auditing on a system, but also audits on all of the systems' suppliers' factories and business. Although a large effort is spent for the PCA task, the system boundary could be extended to only one subprocess chain. On the other hand, using only the IOA could not yield the technology's emission factor within the same sector, since the approach limits to only the sector emission factor. Using an appropriated combined PCA and IOA is not only the win-win approach for defeating the disadvantages of PCA or IOA, but also suitable for the limited data availability in Thailand. However, the approach of combining the PCA and IOA is not a unique approach. Design of a proper combined approach is subjected to the objective and data availability.

Conclusion and Recommendation

Though PCA reflects the reality of a concerned system, it requires extensive effort on energy, materials, services, and emissions auditing through all system-input relevant industries in subprocess chains. Truncation of non-approachable non-identified subprocesses yields significant errors in the LCA, if GHG emissions in those subprocesses are significant. LCA data is country-specific data due to different energy and GHG emission patterns. Performing LCA by PCA in Thailand requires a long-term systematic research program network.

This article suggests that applying a combined PCA and IOA as a suitable approach in the Thai context, the LCA could be evaluated in a short-term period. It is suggested to extend the PCA task as much as PCA data available and incorporate the remaining subprocess with IOA. Though the IOA emission factor faces the error of obtaining an average value, it could be better to fill the gap of non-available PCA data in the indirect process.

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