ORIGINAL ARTICLE

Implications of renewable energy on total CO_2 emissions in the power sector: The full-energy-chains analysis in Thailand

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Abstracts

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Under situation of high imported dependency and limited indigenous resources of primary fossil energy resources, the policy makers have to decide on selection of different power generation technologies to maintain the grid security. Consequently, the fuel mix has been changing over time, and a larger portion of renewable energy resources for electricity generation is currently introduced. In terms of indirect emissions, the change in fuel mix affects not only electricity consumers in the economy, but also the power sector itself. This study examines the impact of introduction of renewable energy to the grid under the 2001 power development plan (PDP2001) on the direct and indirect greenhouse gas (GHG) emissions in Thailand. The energy input-output model is used to estimate the indirect emissions in production process of fuels, materials, and services. Results from the study show that though the direct emission is dominant in the total emissions, the indirect emission is significant. The introduction of more renewable energy plants could reduce the total

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emission factor of the grid, and present significant contribution to the global GHG mitigation. Results of analysis show that total GHGs would be reduced from 773 g $CO_{2\ eqv}$/kWh in 1995 to 563 g $CO_{2\ eqv}$/kWh in 2006.

Key words : full-energy-chains analysis, input-output analysis, renewable energy, GHG mitigation, energy intensity

บทคัดย่อ

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ผลของการใช้พลังงานทดแทนต่อปริมาณแก๊สคาร์บอนไดออกไซด์ในภาคผลิตไฟฟ้า โดยการวิเคราะห์อนุกรมพลังงาน

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ภายใต้สถานการณ์ที่ประเทศมีแหล่งพลังงานฟอสซิลไม่เพียงพอต่อการใช้งาน และต้องพึ่งพาการนำเข้าจากแหล่งพลังงานอย่างมาก เพื่อรักษาความมั่นคงในระบบการผลิตไฟฟ้า รัฐจำเป็นต้องวางแนวนโยบายในการผลิตไฟฟ้าจากเชื้อเพลิงและเทคโนโลยีหลากหลายประเภท และในปัจจุบันได้มีการผลิตไฟฟ้าจากพลังงานทดแทนในอัตราส่วนที่เพิ่มขึ้น ซึ่งการเปลี่ยนแปลงของอัตราส่วนการใช้เชื้อเพลิงนี้จะส่งผลให้ปริมาณการปลดปล่อยแก๊สเรือนกระจกรวมจากทางตรง (โดยโรงไฟฟ้า) และทางอ้อม (จากวัสดุที่ใช้ในการสร้างโรงไฟฟ้า) ของภาคการผลิตไฟฟ้าเปลี่ยนแปลงไป นอกจากนี้ยังส่งผลกระทบทางอ้อมต่อปริมาณของการปลดปล่อยแก๊สเรือนกระจกของภาคอุตสาหกรรมและภาคการใช้ไฟฟ้าอื่น ๆ ด้วย บทความนี้เป็นการศึกษาถึงปริมาณการปลดปล่อยแก๊สเรือนกระจกที่เปลี่ยนแปลงไปของภาคการผลิตไฟฟ้าโดยรวมจากทั้งทางตรงและทางอ้อมจากการเพิ่มอัตราส่วนของพลังงานทดแทนในภาคการผลิตไฟฟ้าโดยพิจารณาถึงแผนการพัฒนาระบบไฟฟ้าปี พ.ศ.2544 (PDP2001) ในการประเมินปริมาณการปลดปล่อยแก๊สทางอ้อมจากการใช้ส่วนประกอบปัจจัยการผลิตต่าง ๆ เช่น พลังงาน วัสดุ หรือบริการ จะประเมินโดยแบบจำลองปัจจัยการผลิตและผลผลิตทางพลังงาน ซึ่งผลการศึกษาพบว่าแม้ว่าค่าปริมาณการปลดปล่อยแก๊สเรือนกระจกทางตรงในภาคการผลิตไฟฟ้ามีค่าสูง แต่ค่าปริมาณการปลดปล่อยแก๊สเรือนกระจกทางอ้อมก็ยังมีผลต่อปริมาณรวม และพบว่าการเพิ่มอัตราส่วนของพลังงานทดแทนในภาคการผลิตไฟฟ้าตามแผนการพัฒนาระบบไฟฟ้าปี พ.ศ. 2544 จะสามารถช่วยลดปริมาณการปลดปล่อยแก๊สเรือนกระจกรวมทั้งทางตรงและทางอ้อมจากภาคการผลิตไฟฟ้าได้จาก 773 g $CO_{2\ eqv}$/kWh ในปี พ.ศ.2538 เหลือเพียง 563 g $CO_{2\ eqv}$/kWh ในปี พ.ศ.2549

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Generally, the fuel mix of energy supply affects energy intensities of final consumption in the economy (Han & Lakshmanan,1994). It non-proportionally affects their total GHG emissions. Since electricity is the basic requirement of every sector in the economy, the fuel mix change in different years would affect energy intensity and GHG emission factors of all final consumption, including the power sector itself.

During the past decade, fuel mix for Thai electricity generation has been changed due to many constraints such as limited indigenous fossil fuel resources, electrical cost, implementation timeframe, and environmental concern. The public awareness of local pollution from the existing lignite power plant retards implementation of the new coal-fired power plants. Preconceiving of natural gas as a clean energy and natural gas exploration in the Gulf of Thailand has induced higher contribution of natural gas in the grid.

Consequently, the high reliance of natural gas decreases supply security in the power generation scheme (EGAT, 2004). The conventional renewable energy plant is hydropower including government-owned plants and purchased power from Lao People's Democratic Republic (EGAT, 2002). Potential of renewable energy is high, i.e. approximately 700 MW of minihydro, 5,000 MW of solar, 1,600 MW of wind, and 7,000 MW of biomass (EPPO, 2004). Private renewable energy plants have been introduced into the grid since 1995 and they have been promoted since 2002 under the small power producers (SPPs) program (EPPO, 2002). Most of them are biomass energy with some of hydropower (EPPO, 2002). The portion of fuels consumed by SPP and others are projected by the current Thai Power Development Plan (PDP2001) (EGAT, 2002). In recent years, the climate change has become the hot agenda in energy planning, and GHG mitigation requires a worldwide joint effort (Van de vate, 1997). Thailand, a non-Annex I country, has published the first "National GHGs Inventory of 1990" in 1997 and updated to 1994 inventory in 2000 (OEPP, 2000; OEPP, 2002). It is reported that the country's CO_2 emission from the energy sector, the largest fossil fuel consumer, is 125.48 tons. The power sector is the major contributor, and the emissions tend to increase with the higher increase of fossil-fired power plants.

In comparison to energy consumption and GHG emissions among different fuel mixes in the power sector, the full-energy-chains analysis is likely to be the only fair approach (Van de vate, 1996). Energy intensity and GHG emission factor in these terms will disclose the total energy and GHGs content embedded in the whole lifecycle of the sector. In an evaluation of total environmental emissions from a considered system, GHGs can be emitted from combustion and non-combustion energy activities. In combustion activities, they are entailed not only from fuel combustion but also from embedded-energy that is indirectly consumed by consumption of materials and services during the lifecycle. Non-combusted-energy emissions are caused by fugitive emissions from production chains of fossil-fuel mining, and by industrial processes such as cement and lime productions (Uchiyama, 1996).

This article presents the impacts of the changes of fuel mix for electricity generation in 1995, 1998, 2001, and 2006, which projected in the recommended plan of the PDP2001 (EGAT, 2002) on the total GHG emission factors. The input-output technique is applied to model the entailed supplying subprocess chains. The results present a comparison of GHG emission factors by different fuel mixes in different periods as projected by the PDP2001.

Status and planned fuel mix of the power sector

Thai electricity consumption in 2000 was 87,932 GWh increasing from 1999 for 8.0% (DEDE, 2001). The total domestic power generation was 95,977 GWh plus net import of 2,773 GWh (EGAT, 2002). In the same period, the total installed electricity generation capacity has increased by 22,593 MW or 11.7% of the total. About 70.3 % of the total installed capacity belongs to the Electricity Generating Authority of Thailand (EGAT) and 29.7% belongs to the private power producers (DEDE, 2001).

The annual peak electrical demand during the 9th National Economic and Social Development Plan (2002-2006) forecasted has been increased from 16,184 MW to 22,552 MW. During the 10th National Economic and Social Development Plan (2007-2011), it is forecasted to be 30,587 MW. Purchased hydro electricity from Lao PDR is 920 MW in 2007. Under electricity supply reform policy the electricity generation authority of Thailand (EGAT) has announced the power purchase from independent power producers (IPPs) since 1994 (EGAT,2002). Most of them are fossil-fired power plants.

EGAT has adopted the power development plan, PDP 99-01, for the year 1999-2001 based on the forecast in the moderate economic recovery case in September 2000. Thereafter EGAT revised the plan to PDP99-02, since new considerable factors emerged, for instance, the production and consumption of natural gas, privatization of EGAT power plants, the delay of plant commissioning, and the uncertainty of IPPs status. Recently, the new power development plan (PDP2001) has been applied since 2001 (EGAT, 2002).

The trend of national grid generation by energy sources from 1991 to 2016 is shown in Table 1. Data of period 1991-2000 are obtained from the Department of Alternative Energy Development and Efficiency (DEDE) and data for period 2001-2016 are the recommended plan and the alternative plan as reported in PDP2001 (EGAT, 2002; EGAT, 2004). Fuel mixes of the grid for period 1995-2001 show the reduction in coal and lignite. The only conventional renewable electrical plant is hydropower including government-owned plants and purchased electricity from Lao PDR. In 2001, natural gas contribution had increased to 62.8% of the total generation. The trend of electricity production from natural gas during 1995-2001 had obviously increased. In the same period fuel oil and diesel oil had decreased. During this period, the renewable plants, particularly by the small power producer (SPP) have played a very important role.

From 2001 to 2006, while imported coal has been introduced in the grid, fuel oil used for electricity production is decreasing and the portion of renewable energies is higher. Diesel and fuel oil have diminished due to their high costs. Though the costs are low, the implementations of lignite and hydro plants are obstructed by higher environmental concerns. Dependency on natural gas reflects the risk of the country generation scheme. The decrease in consumption of natural gas from 2001 to 2016 implies that the policy maker attempts to reduce the use of natural gas for electricity generation. However, the generation mixes in 2011 and 2016 have not been designed yet.

Private-owned renewable energy plants have been contributing to the Thai electricity by SPP subsidizing program since 1998. SPP contribution in 2002 is 313 MW. 89.4% of them are biomass, and 10.6 % is hydro (EPPO, 2002).

In 2003, the Renewable Energy Strategic

Table 1. Percentage of fuel consumption in national grid

	Historical Data[1]										PDP2001 recommended plan[2] [alternative plan]			
	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2006	2011	2016
Diesel Oil	0.25	0.3	1.19	2.08	**3.36**	5.29	2.67	**1.15**	0.56	0.13	-	-	-	-
Fuel Oil	25.18	26.15	27.59	27.6	**27.12**	23.99	20.71	**19.56**	17.2	10.24	**4.2**	**0.9**	0.5	0.4
Natural gas	39.45	40.18	44.09	44.13	**42.34**	42.03	46.32	**51.72**	52.78	56.27	**62.8**	**62.6** [63]	47.90 [42.5]	22 [18.8]
Lignite	25.98	25.95	21.3	19.85	**18.46**	20.02	20.3	**18.3**	17.12	16.52	**15.2**	**11.2**	8.2	4.3 [4.1]
Coal	-	-	-	-	-	-	-	-	-	-	-	**9.9**	13.1	9.7 [9.8]
Hydroa	9.14	7.42	5.84	6.34	**8.38**	8.4	7.72	**5.75**	3.92	6.28	**7.6**	**5.4** [5.2]	12	9.3 [9.1]
SPP (biomass, hydro)	-	-	-	-	**0.33**	0.27	2.29	**3.53**	8.41	10.57	**10.2**	**9.8**	7.5	5.6
Others/new capacity	-	-	-	-	-	-	-	-	-	-	-	-	10.8 [16.2]	48.7 [52.2]

Note: [a] **Domestic and purchased from Lao PDR**
Source: [1] **(DEDE, 2001)**
[2] **(EGAT, 2002)**

Planned was announced. It aims to increase renewable energy penetration from 265 toe in 2002 to 6,540 toes within 8 years (EPPO, 2004). Renewable Energy Portfolio Standard (RPS) has been suggested by the Ministry of Energy in April 2004 to enforce 4% of electricity to be generated by renewable energy. Subsidy of renewable energy in electricity generation is provided.

Methodology and Assumptions

1. Input data and assumptions

The recommended plan of the PDP2001 is analyzed in this article. This article analyzes the fuel mix of the power sector in 1995, 1998, 2001, and 2006. Since the technologies of new power plants during 2011-2016 are not defined, they are not analyzed in this study.

Lifecycle sectoral GHG emission factors in terms of full-energy-chains analysis are derived by I-O table with energy I-O data. Scenarios of fuel mix of the power sector in 2001, and 2006 as planned by PDP2001 are presented in Table 2 to compare with scenarios of 1995 and 1998. To find out the impact of the fuel mix in the power sector, energy consumption patterns in the power sector have changed since 1995. Only 1995 energy I-O data is available for all economic sectors, but the record of fuel mix of the power sector is available together with the plan for fuel mix in the future. In I-O analysis, it is assumed that energy consumption patterns of all other sectors in the whole economy are the same as occurred in 1995. The energy consumption pattern of the power sector in the 1995 sectoral-energy-consumption table is substituted by the expected fuel mix in 2001 and 2006 as stated in PDP2001. The actual fuel mix follows DEDE's report in 1998.

At present, the 1998 I-O table is the most up-to-date. It is assumed that the inter-industrial transaction is constant from 1998 until 2006. Only in the 1995 case, the 1995 I-O table is applied to the 1995 energy I-O data. Sectoral energy consumption in any sector is figured out in an energy unit per monetary output of the sector. All monetary values are converted to 2001 price by using consumer price index (CPI) of Thailand.

2. Evaluation of direct GHG emissions

This article assigns the power sector as an economic sector in the I-O model. The revised 1996 IPCC guidelines (IPCCa, 2001) (IPCCb, 2001) (IPCCc, 2001) that are generally used for preparing national GHGs inventory are applied for estimation of direct GHG emissions from every economic sector. The methods in energy sector of the guidelines are adapted for evaluating emissions by combustion activities and fugitive emissions from production of fossil fuels. Direct emissions from industrial process as reported in the 1994 National GHG Inventory are assumed for all considered cases. Considered GHG's are CO_2, CH_4, and N_2O with the Global warming potential of 1, 21, and 310, respectively (OEPP, 2000).

Direct emissions from fuel combustion are derived from the energy I-O table. Evaluation of

Table 2. Years of input data for energy and economic structure in I-O analysis

Case	Economic structure (I-O table[1])	Sectoral-energy-consumption[2]	Fuel mix in the power sector
1995	1995	1995	1995
1998	1998	1995	1998
2001	1998	1995	2001
2006	1998	1995	2006

Source: [1] **(NESDB, 2001)**
[2] **(NESDB, 2002)**

sectoral direct CO_2 emissions from combustion is presented in Figure 1. In order to avoid double counting of GHG emissions in the economy, only emissions from combustion of domestic primary energies including fossil and renewable energies are taken accounted. Assumption of the same total emission factor as the domestic one is made i.e. the total emission factor of electrical energy from the total primary energy supply is derived early as emission factors of imported secondary energy supply. The term "energetic component" is assigned to adjust the energy I-O elements, since the data of sectoral energy consumption are mostly hidden with the use of fuel for non-combustion. It is a scrutiny in extraction of non-emission for error reduction as presented in Figure 1 and Figure 2. There are no emissions from the use of renewable resources, except CO_2 that emits from biomass combustion. However, the combustion is assumed to be at an equilibrium rate with its growth, consequently, there is no net CO_2 emission. The energy intensity takes into account domestic primary energy, imported primary and secondary energy. Energetic, non-energetic fuels, renewable and non-renewable fuels are considered for their energy and GHG contributions to the total effects.

Fugitive emissions from fossil fuel production, extraction, and delivery are derived from the amount of fossil energies produced in the country by the Global Average Approach in the revised 1996 IPCC guidelines due to the absence of country specific data (IPCCa, 2001) (IPCCb, 2001) (IPCCc, 2001). CH_4 emission can come from production of coal mining and post-mining, oil production, oil refining and storage, natural gas production, processing, transport, distribution, venting and flaring.

3. Input-output model

All energy and emission activities incurred in infinite subprocess chains are evaluated by energy I-O analysis. The partially-closed Leontief inverse (Lenzen, 2001), is performed in order to include the embedded emissions in the extended boundary of imported commodities. However, emission factors of imported commodities are

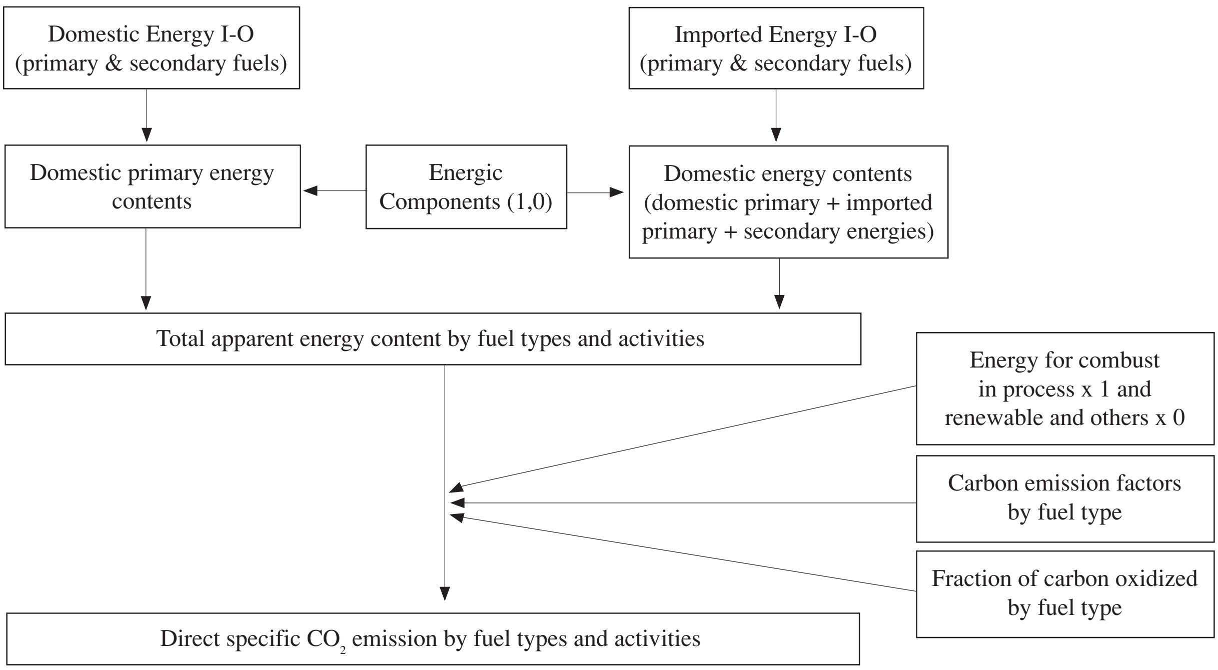

Figure 1. Sectoral direct CO_2 emissions.

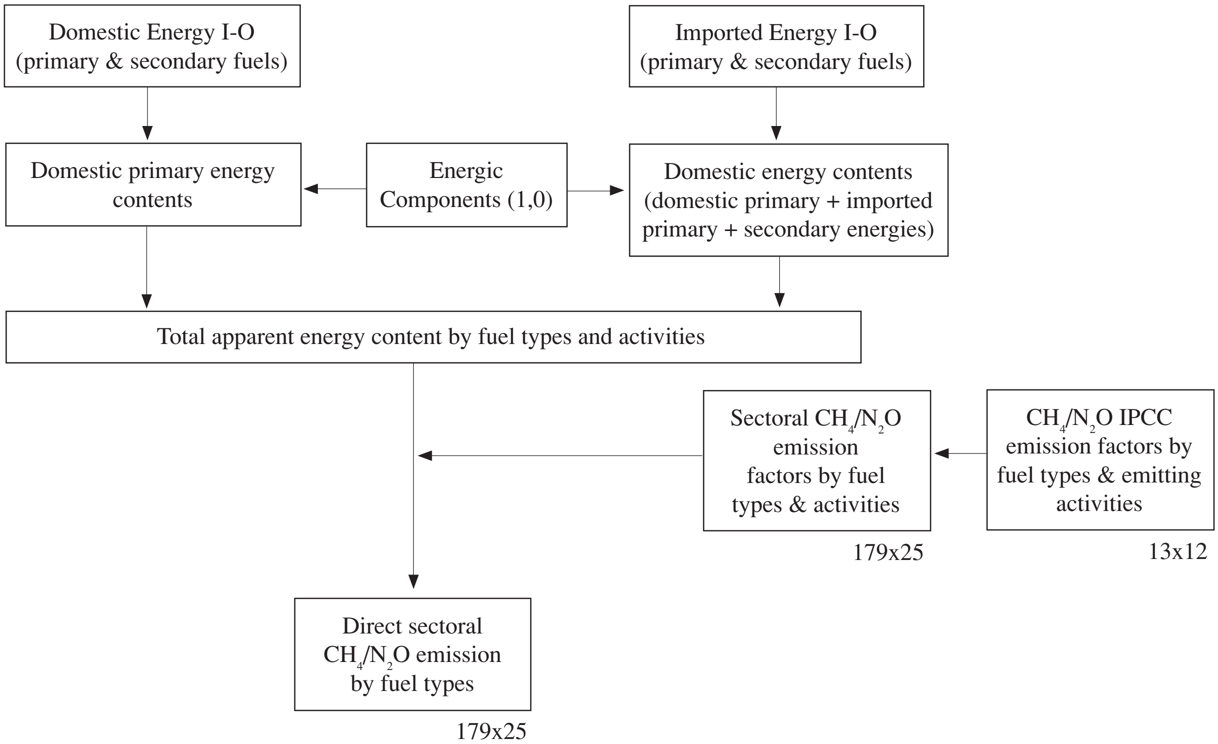

Figure 2. Sectoral direct CH_4 and N_2O emissions.

assumed to be equal to the local ones.

To estimate the indirect emission and energy embedded in all input requirements in the power sector, IOA is used to account all infinite-energy chains caused from production of goods and services in the economy. The direct effect is the direct emission from the main production process of the sector in the economy. The indirect effect is the embedded emission incurred in production of various inputs from other economic sectors in the economy and imported from sectors outside the economy supplied to the sector. An economic sector requires various inputs starting from implementation, operation to decommissioning stages including energy, materials, and services. The indirect emissions generated from all production of all purchased commodities and services are induced by emissions within these inter-industrial transactions. The total effects of sectoral energy intensity and embedded GHG emission factors from all sub-processes in the open economy in terms of full-energy-chains analysis are estimated by multiplying their direct effects with the I-O multiplier. Hybrid units are not applied for the I-O model (Chapman, 1974) (Wright, 1974) (Miller & Blair, 1985), since there is no disparity of energy prices among economic sectors in the Thai economy. In addition, since the capital investment in the Thai I-O table is not internalized into the inter-industrial transaction, capital coefficient could not be considered in this study.

Energy has been used and GHGs have emitted from producing these commodities in the country of origin. GHGs embedded in commodities that are generally imported for the sake of manufacturing requirements in a local producing sector are taken into account by introducing imported I-O matrix, **M**, into the I-O multiplier, then the partially-closed Leontief inverse $[\mathbf{I}\text{-}\mathbf{A}\text{-}\mathbf{M}]^{-1}$ is applied. An average emission factor of the country is assumed for imported fuels since those energy intensities or GHG emission factors could not be particularly specified. Import of secondary energy, such as electricity, is separately accounted for by a concern of embedded energy and GHGs intensity, but approximated by local total intensities of the electricity sector.

Results and Discussions

1. Energy Intensity

Table 3 presents direct energy contents and total energy content, energy intensity, of the power sector in 1995, 1998, 2001, and 2006. The direct energy contents are direct consumption of the power sector. The total energy contents or energy intensity including inter-industrial transactions in the partially-closed economy in terms of full-energy-chains analysis is presented. Indirect energy content is the difference between total energy content and the direct energy content. The indirect energy content implies energy contents embedded in input materials and services in the power sector.

Energy intensities of the power sector are 10.72, 9.27, 9.09, and 9.37 MJ/kWh in 1995, 1998, 2001, and 2006, respectively. The indirect energy contents are 9.18% in 1995, 7.59% in 1998, 7.67% in 2001, and 8.27% in 2006.

The highest contributor of energy intensity in every case is natural gas. Natural gas consumed

Table 3. Direct and total energy content in the power sector by fuel types

Unit: MJ/kWh

	1995		1998		2001		2006	
	Direct	**Total**	**Direct**	**Total**	**Direct**	**Total**	**Direct**	**Total**
Charcoal	-	0.00042	-	0.00034	-	0.00034	-	0.00042
Fuel Wood	-	0.00012	-	0.00011	-	0.00011	-	0.00013
Coal	-	0.00099	-	0.00073	-	0.00073	0.89961	0.93481
Lignite	2.05747	2.20418	1.66267	1.73567	1.38123	1.44345	1.01775	1.06798
Anthracite	-	0.00027	-	0.00016	-	0.00016	-	0.00020
Crude Oil	-	-	-	-	-	-	-	-
Natural Gas	-	-	-	-	-	-	-	-
Condensate	-	-	-	-	-	-	-	-
Paddy Husk	-	0.00116	-	0.00115	-	0.00115	-	0.00139
Bagasse	-	0.00814	-	0.00558	-	0.00558	-	0.00675
Saw Mill Waste	-	0.00012	0.32059	0.33299	0.92688	0.96250	0.89053	0.92479
Pre-Gasoline	-	0.00770	-	0.00731	-	0.00731	-	0.00868
Reg-Gasoline	-	0.00288	-	0.00285	-	0.00285	-	0.00331
Aviation Fuel	-	0.00481	-	0.00572	-	0.00572	-	0.00687
LPG	-	-	-	-	-	-	-	-
Kerosene	-	0.00060	-	0.00047	-	0.00047	-	0.00056
High Speed Diesel	0.38639	0.67114	0.10414	0.39978	-	0.29165	0.01817	0.36611
Low Speed Diesel	-	0.00062	-	0.00055	-	0.00055	-	0.00067
Fuel Oil	2.93613	3.17531	1.77760	1.88991	0.38165	0.44048	0.08178	0.13605
Electricity	-	-	-	-	-	-	-	-
Ethane	-	-	-	-	-	-	-	-
Propane	-	7.09 E-09	-	1.14E-08	-	1.14E-08	-	1.14E-08
LPG	-	0.00062	-	0.00069	-	0.00069	-	0.00083
Others Natural Gas	4.35969	4.64561	4.69941	4.88412	5.70664	5.92994	5.68847	5.91205
NGL	-	-	-	-	-	-	-	-
Direct Energy Contents	**9.73967**	**10.72469**	**8.56441**	**9.26815**	**8.39640**	**9.09370**	**8.59631**	**9.37159**
Indirect Energy Content		**9.18%**		**7.59%**		**7.67%**		**8.27%**

by the power sector appears in the row of "other natural gas". It takes place for 43.32% in 1995, 52.70% in 1998, 65.21% in 2001, and 63.08% in 2006, respectively. On the other hand, contribution of lignite has been decreasing during 1995-2006 i.e. 20.55%, 18.73%, 15.87%, and 11.40%, respectively, but imported coal has been increasing from negligible amount to 9.97% in 2006. Contribution of fuel oil has been reduced during the same period i.e. 29.61%, 20.39%, 4.84%, and 1.45%, respectively.

The contribution of each fuel to the total energy content is similar to the share of each fuel in Table 1. Results of energy intensity are not further discussed in this study, since it is directly related to the fuel mix of the direct energy content. However, it is presented in order to provide debate with the total GHG emissions.

2. Embedded GHG emissions by activities

Table 4 shows GHG emissions in the power sector in different emitting activities i.e. industrial process and fugitive emissions in Section A, and combustion in Section B. Emissions by each case are presented in three categories i.e. 1) direct emissions, 2) total domestic emissions, and 3) total emissions including embedded emissions in net import.

Direct emission factors are 701.8, 572.1, 485.9, and 510.5 g $CO_{2\ eqv}$/kWh in 1995, 1998, 2001, and 2006, respectively. The total emission factors in the partially-closed economy are 773.3, 621.6, 532.1, and 562.7 g $CO_{2\ eqv}$/kWh, respectively. The total emission considered in the closed economy (total domestic emissions) of 760.6, 612.7, 523.3, and 552.5 g $CO_{2\ eqv}$/kWh, respectively. There is no contribution from renewable energy sources in any boundary level of the full energy-chains-analysis. Though biomass energy contributes to the energy intensity, it results in net zero CO_2 emission. Table 4 shows no direct fugitive emissions or direct emissions from industrial process from the main process in the power sector. There are some indirect emissions from these activities but they are not significant to the total emission factor.

The indirect, domestic, GHG contents are 9.3% in 1995, 8.0% in 1998, 8.7% in 2001, and 9.3% in 2006. The indirect, net import, GHG contents are 1.6% in 1995, 1.4% in 1998, 1.6% in 2001, and 1.8% in 2006.

The reduction of direct emissions during 1995-2001 was due to the high decrease in contribution of high-GHG-emitting fuels i.e. lignite, fuel oil and diesel. Contribution of natural gas in the total fuel mix has increased during 1995-2001 and has not changed in 2006. In 2006, although lignite consumption will decrease, coal consumption is introduced to the power generation and its high emission factor consequently yields higher direct emissions. Indirect effects in the closed economy are 58.7, 40.4, 37.3, and 41.8 g $CO_{2\ eqv}$/kWh, respectively. Indirect imported effects, effects by the extended opened-economy, are 12.5, 8.8, 8.3, and 10.2 g $CO_{2\ eqv}$/kWh, respectively.

The change in fuel mix during 1995-2001 yields lower direct GHG emission factors. It affects lower energy intensities and lower total emission factors. But the change in fuel mix during 2001-2006 yields higher energy intensity and higher emission factors. The difference in fuel mix during 1995-2001 yields lower energy intensity, and yields lower emission factors due to higher contribution of renewable energy in the power generation scheme. In 2006, although contribution of renewable energy exists, there is some slight increase of energy intensity and GHG emission factor due to introduction of coal into the grid.

Details of subprocess-chains emissions could express the significance of extending boundary consideration in combustion activity. Each category presents emissions by energy sources. Direct combustion contributes up to 92.4% of the total GHG emissions from production of 1 kWh. The omission errors due to indirect emission in domestic combustion activity for 7.3 %, and due to indirect emission in imported combustion activity for 1.5%. Omission error in consideration of indirect fugitive and industrial process emissions is negligible.

Significance of extending the 1^{st}, 2^{nd}, 3^{rd}, 4^{th}, and 5^{th} subprocess boundary of combustion activity

Table 4. 1995 GHG emissions in the power sector by fuel types and activities.

Unit: g $CO_{2\,eqv}$/kWh

	1995			1998			2001			2006		
	1) Direct combustion	2) Total Domestic & Import	3) Total Domestic	1) Direct combustion	2) Total Domestic & Import	3) Total Domestic	1) Direct combustion	2) Total Domestic & Import	3) Total Domestic	1) Direct combustion	2) Total Domestic & Import	3) Total Domestic
A. Industrial process and fugitive emissions	-	0.193	***0.355***	-	0.177	***0.241***	-	0.177	***0.241***	-	0.177	***0.241***
B. Combustion	**701.764**	**760.435**	**772.950**	**572.065**	**612.478**	**621.326**	**485.855**	**523.167**	**531.813**	**510.457**	**552.297**	**562.461**
Charcoal	-	-	-	-	-	-	-	-	-	-	-	-
Fuel Wood	-	-	-	-	-	-	-	-	-	-	-	-
Coal	-	0.057	0.091	-	0.049	0.068	-	0.049	0.068	83.401	86.450	86.665
Lignite	204.588	217.212	219.173	165.330	171.476	172.587	137.344	142.484	143.529	101.201	105.082	106.193
Anthracite	-	0.001	0.026	-	0.001	0.016	-	0.001	0.016	-	0.001	0.019
Crude Oil	-	-	-	-	-	-	-	-	-	-	-	-
Natural Gas	-	-	-	-	-	-	-	-	-	-	-	-
Condensate	-	-	-	-	-	-	-	-	-	-	-	-
Paddy Husk	-	-	-	-	-	-	-	-	-	-	-	-
Bagasse	-	-	-	-	-	-	-	-	-	-	-	-
Saw Mill Waste	-	-	-	-	-	-	-	-	-	-	-	-
Pre-Gasoline	-	0.464	0.528	-	0.454	0.502	-	0.454	0.502	-	0.538	0.596
Reg-Gasoline	-	0.165	0.199	-	0.171	0.196	-	0.171	0.196	-	0.198	0.228
Aviation Fuel	-	0.253	0.341	-	0.336	0.405	-	0.336	0.405	-	0.403	0.486
Kerosene	-	0.021	0.044	-	0.021	0.034	-	0.021	0.034	-	0.025	0.041
High Speed Diesel	28.333	42.727	49.298	7.636	24.305	29.396	-	16.394	21.467	1.333	20.858	26.942
Low Speed Diesel	-	0.026	0.046	-	0.025	0.041	-	0.025	0.041	-	0.031	0.050
Fuel Oil	224.930	240.652	243.254	136.178	143.160	144.783	29.238	32.373	33.746	6.265	8.881	10.424
Electricity	-	-	-	-	-	-	-	-	-	-	-	-
Ethane	-	-	-	-	-	-	-	-	-	-	-	-
Propane	-	2.38E-7	3.96E-7	-	4.33E-7	6.39E-07	-	4.33E-7	6.39E-07	-	4.33E-7	6.39E-07
LPG	-	0.027	0.039	-	0.033	0.043	-	0.033	0.043	-	0.039	0.052
Other Natural Gas	243.914	258.830	259.910	262.921	272.448	273.254	319.273	330.827	331.766	318.256	329.789	330.764
NGL	-	-	-	-	-	-	-	-	-	-	-	-
Total (A.+B.)	701.764	760.628	773.305	572.065	612.655	621.567	485.855	523.344	532.054	510.457	552.474	562.702
Indirect GHG content		58.864	12.677		40.59	8.912		37.489	8.71		42.017	10.228
		7.61%	1.64%		6.53%	1.43%		7.05%	1.64%		7.47%	1.82%

Table 5. GHG emissions from combustion subprocess by fuel types.

Unit: g $CO_{2\,eqv}$/kWh

Subprocess order	1995 1st	1995 2nd	1995 3rd	1995 4th	1995 5th	1998 1st	1998 2nd	1998 3rd	1998 4th	1998 5th	2001 1st	2001 2nd	2001 3rd	2001 4th	2001 5th	2006 1st	2006 2nd	2006 3rd	2006 4th	2006 5th
Charcoal	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fuel Wood	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Coal	-	0.036	0.024	0.012	0.008	-	0.026	0.018	0.010	0.006	-	0.026	0.018	0.010	0.006	2.428	0.363	0.179	0.106	0.084
Lignite	11.388	1.284	0.594	0.378	0.361	4.990	0.855	0.460	0.302	0.285	4.176	0.742	0.406	0.270	0.259	3.153	0.633	0.366	0.252	0.252
Anthracite	0.007	0.006	0.004	0.003	0.002	0.004	0.003	0.002	0.002	0.001	0.004	0.003	0.002	0.002	0.001	0.005	0.004	0.003	0.002	0.002
Pre-Gasoline	0.228	0.184	0.056	0.028	0.015	0.228	0.160	0.054	0.029	0.015	0.228	0.160	0.054	0.029	0.015	0.270	0.189	0.065	0.035	0.018
Reg-Gasoline	0.081	0.058	0.024	0.019	0.008	0.086	0.052	0.024	0.018	0.008	0.086	0.052	0.024	0.018	0.008	0.100	0.060	0.029	0.021	0.009
Aviation Fuel	0.085	0.072	0.074	0.047	0.027	0.079	0.092	0.098	0.060	0.035	0.079	0.092	0.098	0.060	0.035	0.095	0.111	0.117	0.072	0.042
Kerosene	0.017	0.004	0.005	0.005	0.004	0.016	0.003	0.004	0.004	0.002	0.016	0.003	0.004	0.004	0.002	0.019	0.004	0.005	0.004	0.003
High Speed Diesel	6.250	10.648	2.243	0.955	0.393	4.175	13.379	2.436	1.003	0.370	3.953	13.349	2.422	0.995	0.363	4.627	16.017	2.865	1.178	0.424
Low Speed Diesel	0.020	0.008	0.006	0.005	0.003	0.018	0.007	0.006	0.005	0.003	0.018	0.007	0.006	0.005	0.003	0.022	0.008	0.007	0.006	0.003
Fuel Oil	13.812	1.679	0.987	0.591	0.476	5.362	1.086	0.826	0.478	0.361	2.248	0.653	0.620	0.356	0.260	1.765	0.652	0.676	0.386	0.281
Propane	2.15 E-07	8.41 E-08	3.39 E-08	1.76 E-08	1.17 E-08	3.86 E-07	1.25 E-07	4.69 E-08	2.38 E-08	1.56 E-08	3.86 E-07	1.25 E-07	4.69 E-08	2.38 E-08	1.56 E-08	3.86 E-07	1.25 E-07	4.69 E-08	2.38 E-08	1.56 E-08
LPG	0.013	0.008	0.005	0.006	0.003	0.015	0.009	0.007	0.007	0.003	0.015	0.009	0.007	0.007	0.003	0.018	0.011	0.008	0.008	0.003
Other Natural Gas	13.279	1.239	0.516	0.306	0.251	7.707	1.127	0.550	0.336	0.272	9.348	1.355	0.659	0.401	0.325	9.329	1.364	0.690	0.407	0.329
Subtotal	***45.180***	***15.225***	***4.539***	***2.354***	***1.549***	***22.680***	***16.799***	***4.487***	***2.254***	***1.361***	***20.170***	***16.450***	***4.321***	***2.155***	***1.280***	***21.831***	***19.415***	***5.011***	***2.476***	***1.450***
	5.8%	2.0%	0.6%	0.3%	0.2%	3.6%	2.7%	0.7%	0.4%	0.2%	3.8%	3.1%	0.8%	0.4%	0.2%	3.9%	3.5%	0.9%	0.4%	0.3%

Table 6. 2006 GHG emissions in the power sector by gases

Unit: g $CO_{2\ eqv}$/kWh

	CO_2			CH_4			N_2O		
	Direct	**Total Domestic**	**Total Domestic & Import**	**Direct**	**Total Domestic**	**Total Domestic & Import**	**Direct**	**Total Domestic**	**Total Domestic & Import**
A. Industrial process and fugitive emissions	-	0.144	***0.208***	-	0.002	***0.002***	-	-	-
B. Combustion									
Charcoal	-	-	-	-	-	-	-	-	-
Fuel Wood	-	-	-	-	-	-	-	-	-
Coal	83.401	86.450	86.665	-	-	-	-	-	-
Lignite	100.936	104.807	105.918	0.0006	0.001	0.001	0.0008	0.0008	0.0008
Anthracite	-	1.12E-03	0.019	-	9.09E-09	1.94E-07	-	-	-
Crude Oil	-	-	-	-	-	-	-	-	-
Natural Gas	-	-	-	-	-	-	-	-	-
Condensate	-	-	-	-	-	-	-	-	-
Paddy Husk	-	-	-	-	-	-	-	-	-
Bagasse	-	-	-	-	-	-	-	-	-
Saw Mill Waste	-	-	-	-	-	-	-	-	-
Pre-Gasoline	-	0.538	0.595	-	1.83E-07	2.34E-07	-	9.62E-07	1.72E-06
Reg-Gasoline	-	0.198	0.227	-	1.09E-07	1.65E-07	-	1.74E-07	3.04E-06
Aviation Fuel	-	0.403	0.486	-	1.14E-08	1.37E-08	-	-	-
LPG	-	-	-	-	-	-	-	-	-
Kerosene	-	0.025	0.040	-	3.60E-08	1.51E-07	-	9.43E-07	3.96E-06
High Speed Diesel	1.333	20.800	26.845	5.45E-07	1.42E-05	2.11E-05	-	1.89E-04	0.0003
Low Speed Diesel	-	0.031	0.049	-	2.61E-08	1.47E-07	-	5.13E-07	3.66E-06
Fuel Oil	6.264	8.879	10.421	0.0001	9.71E-05	1.45E-04	-	1.02E-06	1.21E-06
Electricity	-	-	-	-	-	-	-	-	-
Ethane	-	-	-	-	-	-	-	-	-
Propane	-	-	6.39E-07	-	-	-	-	-	-
LPG	-	0.039	0.052	-	4.64E-07	6.70E-07	-	6.79E-07	7.90E-07
Others Natural Gas	317.528	329.034	330.007	0.035	0.036	0.036	-	-	-
NGL	-	-	-	-	-	-	-	-	-
Total Combustion	**509.462**	**551.204**	**561.324**	**0.035**	**0.037**	**0.037**	**0.0008**	**0.0010**	**0.0012**
% of total GHG emissions	90.5%	98.0%	99.8%	0.0062%	0.0066%	0.0066%	0.0001%	0.0002%	0.0002%

is presented by Table 5. Omission approximately 5% would occur for consideration of the power plant lifecycle boundary up to the 1st subprocess, and it would be approximately 9% for consideration only the main combustion process. Consideration up to the 5th subprocess yields approximately 0.3% omission.

Table 6 presents the embedded emissions of different GHG's i.e. CO_2, CH_4, and N_2O in 2006 in terms of consideration level and energy sources. Significant GHG emission factor contributor is CO_2 emissions. Total CO_2 emission takes 99.8% of the total emission factor. Total contribution of CH_4 is only 0.2% and total contribution of N_2O is negligible. Most of CH_4 emission contributor comes from direct combustion of natural gas.

The changes of fuel mix in the power sector during 1995-1998 results in lower energy intensity and lower emission factors in the power sector. Consequently, their energy intensity and emission factors are lower. During 1998-2001, direct and indirect factors are decreased. From 2001 to 2006, with higher direct energy content and higher direct emissions, energy intensity and emission factors are increased. Among all cases, indirect emissions and indirect energy content in 1995 is the highest.

Conclusions and Recommendations

Total GHG emission factor of the Thai power sector in terms of full-energy-chains analysis is expected to reduce from 773 g $CO_{2\,eqv}$/kWh in 1995 to 563 g $CO_{2\,eqv}$/kWh in 2006. This successful mitigation is caused from increasing contribution of renewable energy to the power generation scheme starting from 1998, 2001 and 2006. The high increase in electricity demand makes the PDP plan inevitably select imported coal up to 10% to the grid and finally its total GHG contribution is 15.4%.

The study also reveals the significance of inclusion of the indirect effect in the full-energy-chains analysis. Indirect effect in combustion activity, particularly in the first and second subprocess chains, is significant to the total effect.

Though the energy related GHG has to be derived from the amount of energy consumption, there is no linear proportionality between "energy intensity" and "greenhouse gases intensity". Among different fossil fuels, coal and lignite release higher GHG amount than other fuels. Zero GHG content could be accounted from contribution of renewable energy by the same energy content. Delineation of most sectors into subprocess orders and activities reveals that we could not neglect indirect effects. The enforcement of renewable energy policy in Thailand for electricity production would result in lower GHG emission factor.

Since electricity is the basic requirement of the economy, lower emission in electricity itself would affects lower GHG emission factor of all intermediate and final consumptions. Finally, the total energy-related GHG emissions of the country would be mitigated. Since this study analyzes fuel mix by their contribution to the electricity sector, but does not mention variation in power plant technology. Improvement could be done by revision detailed structure in the energy I-O analysis.

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