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ENERGY EFFICIENCY AND ENVIRONMENTAL EMISSIONS REDUCTION: A FACTOR DECOMPOSITION ANALYSIS

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ABSTRACT

This paper analyzes the role of selected supply- and demand-side energy efficient technologies in the power sector development in a developing country using a long-term integrated resource planning (IRP) framework. It also analyzes the factors affecting the changes in total CO_2 *and* SO_2 *emission intensities of power generation during the planning horizon using the Divisia decomposition approach. The study shows that the use of efficient demand-side technologies would reduce power sector emissions of* CO_2*,* SO_2 *and* NO_x *by about 8.9%, 6.6% and 9.7%, respectively during 2005-2019. Furthermore, the study shows that* CO_2 *emission intensity would be reduced at an average annual rate of 5.5% during 2005-2019 in the business as usual case and by4.5% in the energy efficiency improvement case. The decline in* CO_2 *emission intensities would take place mainly due to generation efficiency improvements in the business-as-usual (BAU) case, and due to the changes in both power generation efficiencies and generation mix in the energy efficiency improvement (EEI) case.*

Key words: integrated resource planning, energy efficiency, energy and the environment

I. INTRODUCTION

Energy efficiency improvement in both supply- and demand-sides has been considered as an effective option for reducing the adverse environmental impacts of electricity generation. The role of energy efficiency improvement has been considered in a number of existing studies (see e.g., [1] and [2]). These studies have assessed potential energy savings due to efficiency improvements in the demand-side in various economic sectors. However, the assessments in these studies were based on the static analysis of potential savings in energy use and peak load from the demand-side only and not on a long-term planning exercise that considers both supply- and demand-side options simultaneously.

This study examines the role of efficiency improvement in the demand- and supply-side in the power sector in Thailand from a long-term integrated resource planning (IRP) perspective (hereafter "energy efficiency improvement" (EEI) case). It analyzes the effects of adopting cost-effective energy efficient demand-side technologies on electricity generation and generation capacity avoided as well as total costs during the planning horizon (2005-2019) as compared to the traditional, i.e., supply based electricity planning (hereafter "business as usual" (BAU) case). More importantly, it assesses the relative contributions of energy efficient demand-side technologies to changes in CO_2, SO_2 and NO_x emissions from the power sector under the EEI case from that under the BAU case. Furthermore, the paper examines the roles of changes in fuel mix and generation efficiencies in the changes in overall CO_2 and SO_2 emissions intensities (defined as the amount of emission per unit of thermal power generation) over time under both the BAU and EEI cases.

II. METHODOLOGY

2.1 The IRP Model

In this study the least cost supply- and demand-side technologies are determined through a long term IRP model which is formulated as a mixed integer linear programming problem. For a detailed mathematical formulation of the model, see [3].

2.2 Decomposition of Total Change in Pollutant Emissions with EEI

Note that a change in the level of emission in the EEI case over that in the BAU case can take place due to changes in fuel- and technology-mixes in power generation besides that due to the reduction in electricity generation with the adoption of efficient energy using equipments. Hereafter, the change in emission purely due to the supply-side changes (i.e., changes in generation efficiency and fuel-mix) is called the "supply-side effect". The change in emissions due to changes in the level of electricity demand (and hence generation) (while the fuel-mix and generation efficiencies remaining the same as in the BAU case) is called the "demand-side effect". We assess the relative contribution of supply and demand-side effects, following the methodology described in [3].

2.3 Decomposition of Pollutant Emission Intensities Over Time

The factor decomposition analysis in the literature is focused on examining the historical changes in emission intensity [5]. In this study, the decomposition approach has been used to analyze the changes in emission intensities during the planning horizon. A change in overall power sector emission intensity can be decomposed into three components, *i.e.*, the contribution of changes in fuel intensities of generation (hereafter “fuel intensity effect”), changes in structure of electricity generation (hereafter “fuel mix effect”), and changes in fuel qualities, e.g., heat value, carbon and sulfur content (hereafter “fuel quality effect”). The Log-Mean Divisia Index (LMDI) method is used in this study, as it is more accurate for factor decomposition than other techniques [4]. The mathematical formulation of the decomposition method in the case of CO_2 emission intensity is as follows:

Nomenclature:

e_t = CO_2 emission intensity of thermal power generation in year t

E_t = total CO_2 emissions from thermal power generation for year t

E_{it} = emission of CO_2 from power generation based on fuel type i in year t

c_{it} = carbon content of fuel type i (expressed as a fraction of total weight of fuel) in year t

k = conversion factor (from carbon to carbon dioxide)

F_{it} = amount of fuel type i used for power generation in year t

Q_{it} = electricity generation based on fuel i in year t

Q_t = total thermal electricity generation

f_{it} = fuel intensity of power generation from fuel i in year t ($=F_{it}/Q_{it}$)

g_{it} = share of electricity generation from fuel type i in year t ($= Q_{it}/Q_t$)

The total CO_2 emission intensity in year t is expressed as:

$$e_t = \frac{E_t}{Q_t} = \sum_i k \frac{c_{it}F_{it}}{Q_{it}} \frac{Q_{it}}{Q_t} = \sum_i k c_{it} f_{it} g_{it} \qquad (1)$$

Following [5] a change in total CO_2 emissions from the thermal generation (in logarithmic terms) between years t and t-1 can be decomposed as:

$$\ln\frac{e_t}{e_{t-1}} = \sum_i \tilde{w}_{it*} \ln\frac{f_{it}}{f_{it-1}} + \sum_i \tilde{w}_{it*} \ln\frac{g_{it}}{g_{it-1}} + \sum_i \tilde{w}_{it*} \ln\frac{c_{it}}{c_{it-1}} \qquad (2)$$

where,

$$\tilde{w}_{it*} = \frac{L(w_{it}, w_{it-1})}{\sum_i L(w_{it}, w_{it-1})} \quad \text{with} \quad \mathrm{w_{it}} = \frac{\mathrm{c_{it} * f_{it} * g_{it}}}{\sum_i \mathrm{c_{it} * f_{it} * g_{it}}}$$

and

$$L(w_{it}, w_{it-1}) = (w_{it-1} - w_{it}) / \log(w_{it-1} / w_{it}) \qquad (3)$$

$\tilde{w}_{it}$ is known as the log-mean weight function [4]. The first term in the right-hand side (RHS) of Equation (2) represents the fuel intensity effect. The second term expresses the generation mix effect while the third term represents the fuel quality effect. However, in this analysis, fuel quality is assumed to be unchanged during the study period (i.e., the third term is ignored).

Thus the CO_2 emission index (e_t/e_{t-1}) based on Equation (2) can be represented as:

$$\frac{e_t}{e_{t-1}} = \exp\left(\sum_i \tilde{w}_{it*} \ln\frac{f_{it}}{f_{it-1}}\right) . \exp\left(\sum_i \tilde{w}_{it*} \ln\frac{g_{it}}{g_{it-1}}\right) \qquad (4)$$

III. POWER SECTOR IN THAILAND

Electricity Generating Authority of Thailand (EGAT) is responsible for electricity generation and transmission while Metropolitan Electricity Authority (MEA) and Provincial Electricity Authority (PEA) are responsible for power distribution. The system peak demand recorded in April 5, 2000 was 14,918 MW. As of April 2000, thermal generation accounted for 64.5% of the total electricity generation with the rest coming from hydropower and power purchase [6]. Total electricity consumption by economic sectors in 1997 was 82,429 GWh, in which the industrial sector accounted for the highest share (43%), followed by the commercial sector (35%), the residential sector (21%) and others (1%) [7].

Thailand has been implementing various DSM programs since 1993. These programs included efficiency improvement in residential and commercial lighting, refrigerators and air-conditioners, as well as industrial motors. The use of compact fluorescent lamps and slim tube fluorescent lamps has been one of the successful DSM programs in Thailand. In addition, there are programs for attitude creation and information dissemination to promote energy efficiency improvement. By the end of December 1998, DSM programs in Thailand have resulted in saving of 503 MW of peak demand and 2,345 GWh of electrical energy [8]. .

IV. DATA AND ASSUMPTIONS

All cost figures in the study are expressed as economic costs at 2001 US dollars. A real discount rate of 8.25% is used in the analysis. System reliability is represented by reserve margin of 25%. The load forecast used in this study is that based on the “Moderate Economic Recovery” scenario [6]. The system load factor is assumed to increase from 72.51% in 2005 to 79.81% in 2016, and then decrease to 76.88% in 2019 [9]. In the EEI case, nine DSM options are considered as listed in Table

1 -- three in the residential sector, one in the commercial sector and five in the industrial sector.

Data on existing, committed and candidate power plants used in this study are adopted from [8]. Candidate plants comprise of 100 MW and 200 MW gas turbines, 700 MW coal-fired units, 1000 MW coal-fired units, 1000 MW oil-fired units, and 600 MW combined cycle power plants. Two types of clean coal generation technologies are considered in this study, *i.e.*, integrated gasification combined cycle (IGCC) and pressurized fluidized bed combustion (PFBC), each with unit size of 165 MW and 43% efficiency as reported in the available literature [10].

Table 1. Demand side management options considered

Sector / DSM Options*
Residential: - Replacement of 60W ILs with 13W CFLs - Replacement of inefficient refrigerators with efficient refrigerators - Replacement of inefficient ACs with efficient Acs
Commercial: - Replacement of inefficient ACs with efficient Acs
Industrial: - Replacement of below 5 hp standard motors with EEMs - Replacement of 5-20 hp standard motors with EEMs - Replacement of 20-50 hp standard motors with EEMs - Replacement of 50-125 hp standard motors with EEMs - Replacement of 125-500 hp standard motors with EEMs

* Note: IL: Incandescent lamp, CFL: compact fluorescent lamps, EEM: energy efficient motors, AC: air conditioners,

The description of BAU and EEI cases considered in the study is as follows:

Case 1: Business as Usual (BAU)

In this case, only supply-side options are considered in the generation capacity expansion planning exercise to meet the projected energy demand. Efficient supply-side technologies (*i.e.,* IGCC and PFBC) are also included as the candidate power plants in the study. This case will be used as the reference to compare the changes in the levels of generation, generation capacity and emissions of air pollutants when energy efficient end use technologies are considered.

Case 2: Energy Efficiency Improvement (EEI)

In EEI case, the optimal development plan of the power sector is obtained by considering both supply- and demand-side options to meet the same projected energy "demand" as in the BAU case.

V. POWER SECTOR PLANNING IMPLICATIONS

In the BAU case, 33,960 MW of new generation capacity would be added during 2005-2019, comprising of 16,400 MW oil-fired power plants (48.3%), 11,400 MW combined-cycle power plants (33.6%), 4,000 MW coal-fired power plants (11.8%), 1,460 MW hydro and pump storage power plants (4.3%), and 700 MW gas turbines plants (2.1%).

With the introduction of efficient demand-side options (i.e., in the EEI case), requirement for generating capacity addition would be by 21.5% as compared to from that in the BAU case reduced due to efficient demand-side technologies. Of the total generating capacity added during the planning horizon, combined-cycle power plants accounted for 42.8%, followed by oil-fired power plants (36.8%), coal-fired power plants (15.0%), hydro and pump storage power plants (5.4%). Table 2 shows the total electricity generation and generation capacity by type of fuel during 2005-2019. As can be seen, thermal power generation would continue to dominate in both cases. It should be noted that with the introduction of energy efficient demand-side technologies, 7,300 MW of generation capacity and 347 TWh of electricity generation would be avoided.

Clean coal power plant options (*i.e.*, IGCC and PFBC) are not selected during 2005-2019 because of their relatively high capacity cost at the present. However, sensitivity analysis shows that if the capacity cost of clean coal technologies were to fall to 1,200 $/kW or their thermal efficiency were to increase to 45%, these plants would be cost-effective and added to the power system during the period.

Table 2. Total electricity generation and generation capacity during 2005-2019

Case	Share in Capacity (%)		Total (MW)
	Thermal	Hydro	
BAU	82.1	17.9	52,061
EEI	72.9	20.8	44,761
	Share in Generation (%)		Total (GWh)
BAU	89.8	10.2	3,555,847
EEI	88.8	11.2	3,208,137

All efficient DSM options were found to be cost-effective during 2005-2019. Sensitivity analysis shows that even if the cost of DSM option were increased by 40%, all DSM options would still be cost-effective and selected. Total electricity generation avoided by DSM options accounts for 9.1% of the total electricity generation requirement under the BAU case. Among the DSM options considered, efficient air-conditioners in the commercial sector has the highest share in total electricity generation avoided (62.02%), followed by efficient motors in the industrial sector (17.27%), efficient air-conditioners

(12.98%), efficient refrigerators (7.28%) and efficient lighting in the residential sectors.

How would EEI in the demand-side affect the utilization of the power generation capacity? In particular, would capacity utilization improve with the adoption of efficient demand-side technologies? To answer this question, the weighted average capacity factor (WACF) of the power system under the BAU case is found to be 69.41%, which is lower than that in EEI case (69.66%). Similarly, the weighted average load factor (WALF) is found to increase in the EEI case (89.42%) as compared to that in the BAU case (88.38%).

As total installed generation capacity and plant-mix change with the introduction of efficient demand-side options, so would the reliability of electricity generation system. Also, the values of weighted average loss of load probability (LOLP) and total expected energy not served (EENS) during 2005-5019 under the two cases are found to increase with the introduction of cost-effective energy efficient demand-side technologies. That is, with the introduction of efficient demand-side technologies, the system reliability of the Thai Power System in the EEI case would be reduced the minimum allowable reserve margin constraint given.

The total expansion cost (including capacity cost, O&M cost) in the BAU and EEI cases and their break-down are presented in Table 3. As can be seen, total cost in the EEI case is 7.6% lower than that in the BAU case. This clearly shows the benefits of efficiency improvement in the demand-side. The share of capacity cost is 10.4% of the total cost under the BAU case, while it is only 8.8% under the EEI case.

Table 3. Breakdown of cost during the planning horizon, million US$ at 2001 prices(*)

	BAU	EEI
Capacity cost	5,047.5	3,943.2
Fuel and O&M cost	43,592.4	39,571.3
DSM cost	--	1,339.2
Total cost	48,639.9	44,913.7

* All costs are expressed in discounted terms

VI. ENVIRONMENTAL IMPLICATIONS

The total emissions of air pollutants during 2005-2019 under the two cases are presented in Table 4.

Table 4. Total emissions of CO_2, SO_2 and NO_x during the planning horizon (million tons)

Pollutants	BAU	EEI
CO2	2,072.3	1,886.9
SO_2	18.1	16.9
NO_x	7.2	6.5

With the use of efficient demand-side technologies, total emissions of CO_2, SO_2 and NO_x in the EEI case would be reduced by 8.9%, 6.6% and 9.7% respectively as compared to those in the BAU case.

Table 5 shows the decomposition of the total change in emission in the EEI case over that in the BAU case during the planning horizon following the methodology described in Section 2.2. The table shows that demand-side effects would contribute towards the reduction of CO_2, SO_2 and NO_x emissions. The supply-side effect is found to have an adverse effect on the level of all emissions. This is because, the shares of diesel-fired combined cycle power plants in total generation capacity are higher in the EEI case than that in the BAU case.

Emissions avoided by the use of different efficient end-use technologies are calculated on the basis of their shares in total generation avoided. It is found that the commercial sector AC would have the dominant share of 62.02% of total emission mitigation, followed by EEMs in the industrial sector (17.27%), efficient air-conditioners (12.98%), efficient refrigerators (7.28%) and efficient lighting (0.46%) in the residential sector.

Table 5: Breakdown of total pollutant mitigation during the planning horizon (thousand tons)

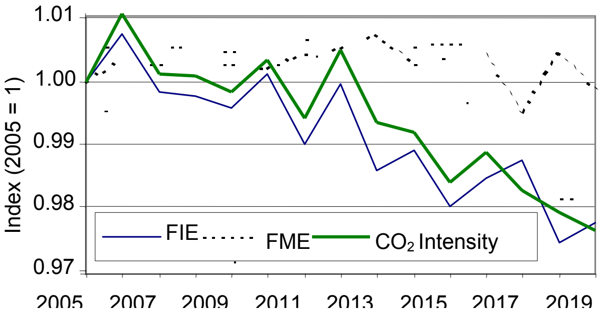
Mitigation due to	CO_2	SO_2	NO_x
· Demand-side effect	187,974.6	1,557.8	653.0
· Supply-side effect	-2,303.4	-486.0	-21.1
· Joint effect	-218.6	26.6	3.1
Total	185,452.6	1,098.4	635.0

VII. FACTORS AFFECTING EMISSION INTENSITIES

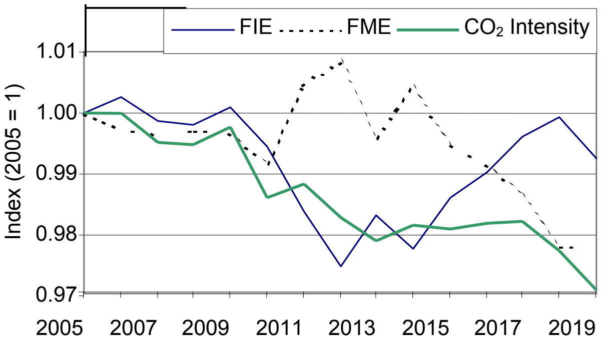
It would be interesting to know the changes in emission intensities of the key pollutant emissions from power generation and the factors affecting those changes. In this study, the change in emission intensity is broken down into two key underlying factors, i.e., the fuel intensity effect (FIE) and the fuel mix effect (FME). The fuel intensity and fuel mix-effects as well as the and total power sector CO_2 emission intensity under the two cases are shown in the Figures 1(a) and 1(b).

In the BAU case, CO_2 emission intensity tends to increase during 2005-2007 and is influenced by both FIE and FME as more electricity is generated from coal- and oil-based power plants. From 2007 onwards, FIE would contribute to the reduction of CO_2 emission intensity, indicating the positive role of more efficient thermal power plants. This is due to the addition of efficient power plants (e.g., new combined cycle power plants with efficiency of 47% and coal-fired power plants of 38%) with some of the existing low efficiency thermal power plants kept as reserve plants.

How would FIE and FME affect the overall CO_2 emission intensity with the inclusion of efficient demand-side technologies? As can be seen from Figure 1(b), both FIE and FME contribute to the reduction in CO_2 emission intensity during 2005-2010. During 2010 - 2016, the emission intensity is found to be influenced mainly by FIE due to the addition of and electricity generation from new combined-cycle power plants. CO_2 emission intensity reduction during 2017-2019 was found mainly due to the FME.



(a) BAU Case

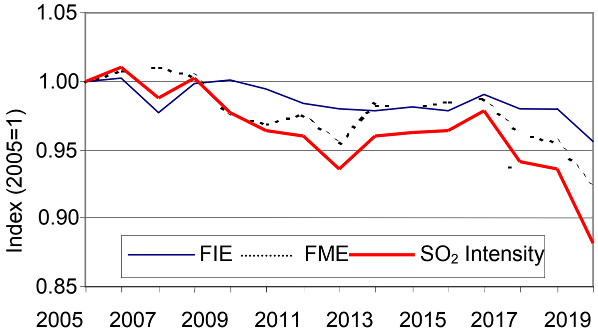


(b) EEI Case

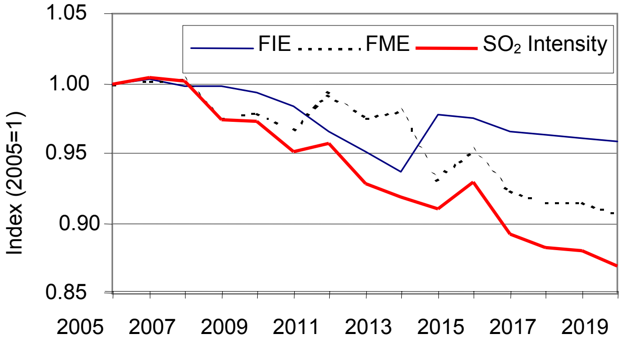
Figure 1: Decomposition of power sector CO_2 emission intensity changes

Similar analysis was carried out for the change in SO_2 emission intensity. It is shown in Figure 2(a) that both FIE and FME would contribute to the reduction of total SO_2 emission intensity in the BAU case, while under the EEI case it is due to FIE during 2005-2014 and due to FME thereafter.

Following an approach similar to that described in Section 2.3, the power sector energy intensity changes during 2005-2019 have been decomposed into fuel intensity effect (FIE) and fuel mix effect (FME) components. The FIE and FME components are shown along with the overall energy intensity of electricity generation under the BAU and EEI cases in Figures 3(a) and 3(b).

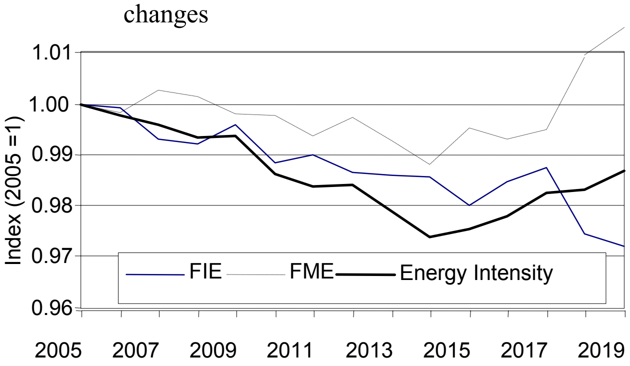


(a) BAU Case

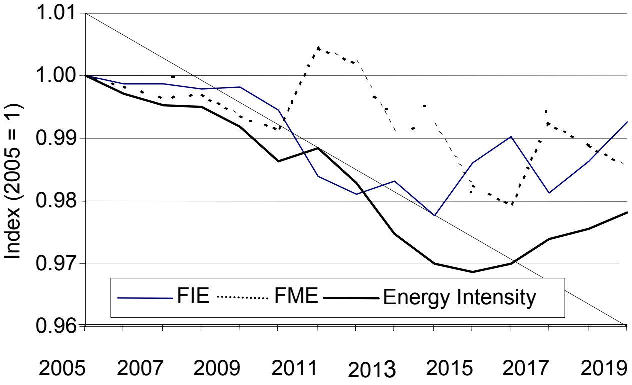


(b) EEI Case

Figure 2: Decomposition of power sector SO_2 intensity changes



(a) BAU Case



(b) EEI Case

Figure 3: Decomposition of power sector energy intensity changes

As can be seen, the energy intensity would decline during 2005-2014 in the BAU case and during 2005-2015 in the EEI case. Thereafter, it would increase slightly due to the addition of more coal-fired power plants. In the BAU case, energy intensity is mainly influenced by FIE indicating the positive role of more efficient thermal power plants. This could be explained by the addition of efficient power plants (e.g., combined cycle and coal-fired power plants with efficiency of 47% and 38% respectively). In the EEI case, both changes in FIE and FME would affect the changes in energy intensity during the planning horizon.

VIII. CONCLUSION

The study shows that, generation capacity of 7,300 MW and electricity generation of 320,710 GWh could be avoided in Thailand with the introduction of cost effective energy efficient demand-side technologies during 2005-2019. The adoption of efficient air conditioners in the commercial sector would play the dominant role in electricity generation avoided as it would account for about 62% of total generation avoided. This is followed by EEMs in the industrial sector (17%), and efficient air-conditioners in residential sector (13%). Total cost during the planning horizon in the EEI case would be reduced by 7.6% as compared to that in the BAU case.

This study also shows that energy efficiency improvements in the power sector would reduce CO_2, SO_2 and NO_x emissions by 8.9%, 6.6% and 9.7%, respectively, during the planning horizon, as compared to that in the BAU case. The decomposition analysis shows that the changes in total environmental emissions (CO_2, SO_2, NO_x) in the EEI case are mainly due to changes in the level of electricity generation resulting from the use of efficient DSM appliances (i.e., the demand-side effect). The supply-side effect is found to have an adverse effect on the emissions of the pollutants considered. The Divisia decomposition analysis of changes in emission intensity over time shows that in both BAU and EEI cases, the improvements in generation efficiency (due to the addition of more efficient power plant capacities) would contribute towards reduction of CO_2 and SO_2 emissions intensities while the fuel mix effect would tend to have the opposite effect. The study also shows that the overall energy intensity of the power generation in Thailand would be decreasing during 2005-2015 and increase thereafter under both BAU and EEI cases.

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REFERENCES

[1] C. W. Gellings, A. Faruqui & K. Seiden, 1991. Potential Energy Savings from Efficient Electric Technologies. *Energy Policy. 19*(3), 1991, 217-230.

[2] M. D. Levine & S. Meyers, The Contribution of Energy Efficiency to Sustainable Development in Developing Countries, *Natural Resources Forum, 16*(1) 1992, 19-26.

[3] R. M. Shrestha, H. Samarakoon & R. Shrestha, *Assessment of Demand- and Supply-Side Technologies for Greenhouse Gas Mitigation from an Integrated Planning Perspective* (mimeo, Asian Institute of Technology, Bangkok, Thailand, 2000).

[4] B. W. Ang & F. L. Liu, *A New Decomposition Method: Perfect in Decomposition and Consistent in Aggregation*, Energy, 26(6), 2001, 537-548.

[5] R. M. Shrestha and G. R. Timilsina, Factors Affecting CO_2 Intensities of Power Sector in Asia: A Divisia Decomposition Analysis, *Energy Economics*, *18*(3), 1996, 283-293.

[6] Electricity Generating Authority of Thailand (EGAT), *EGAT Power Development Plan* (System Planning Department, EGAT, Thailand, 2000).

[7] Department of Energy Development and Promotion (DEDP), *Electric power in Thailand* (DEDP, Ministry of Science Technology and Environment, Thailand, 1997).

[8] Electricity Generating Authority of Thailand (EGAT), *DSM in Thailand: Experiences and Perspective* (Demand Side Management Office, EGAT, Thailand, 1999).

[9] Sirindhorn International Institute of Technology (SIIT), *Least cost supply-side options for mitigating GHGs and other harmful emissions from the power sector subject to emission target* (mimeo, SIIT, Thailand, 2000).

[10] E. S. Tavoulareas and J. P. Charpentier, *Clean Coal Technologies for Developing Countries, World Bank Technical Paper No. 286, Energy Series* (The World Bank, Washington D.C., USA, 1995).