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EVALUATION OF EMISSION AND REDUCTION OF GREENHOUSE GASES FROM UPSTREAM PETROCHEMICAL INDUSTRY IN THAILAND

The study aimed to determine the baseline and indicators for the emission of greenhouse gases (GHG) and to evaluate the effectiveness of GHG mitigation measures in Thai upstream petrochemical plants. During 2005–2010, the upstream production had an annual demand for energy in the range of 110 000–150 000 TJ, ca. 5–6% of the total Thailand energy consumption. The proportion of energy consumption for producing olefin and aromatic products is 73 and 14%, respectively. The amount of GHG emissions equalled approximately 7–9 Mt CO_2 eq. This represents a 3% portion of the total GHG emissions of Thailand, separating into the olefin and aromatic products, around 69 and 18%, respectively. The ratios of GHG emission came from fuel combustion of 59%, steam consumption (28%), electricity consumption (10%) and flare (3%). The carbon intensity of upstream products in the olefins and aromatics' groups had the range of 1.125–1.309 and 0.518–0.667 t CO_2 eq/t, respectively. It was likely that the carbon intensity during the period of 2005–2010 was lowered as the industry sector took measures to improve energy conservation and developed their production processes. The GHG mitigation measures by energy conservation were already implemented including fuel saving (67%), steam saving (23%) and electricity saving (10%).

I. INTRODUCTION

From the agenda of the IPCC 2007 meeting, the reduction of greenhouse gasses (GHG) emission will use the Sectoral Approach mechanism. This is a new mechanism for controlling the emissions of GHG within the international manufacturing sector of the same industry, so both developed and developing countries will be able to participate in further reducing GHG emissions. The chemical and petrochemical industries

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are among priority sectors which should deal with measures to reduce GHG using the Sectoral Approach [1]. According to the report by WRI in 2005 [2], chemical and petrochemical industries emitted the highest amount of GHG, contributing up to 23% of total emissions from industry and 5% of the world's emissions. Chemical and petrochemical industries are also industries ranked second in the world for energy demand in production. These factors contribute to the petrochemical industry being a sector likely to initiate international measures to reduce GHG voluntarily under the Sectoral Approach mechanism.

Thailand was ranked as the 31st GHG emitter in the world with emissions of GHG estimated in 2005 at 377 039 kt CO_2 eq [2, 3], represented as a proportion of 0.95% of the total world's emissions. The significant sources of GHG in Thailand come from the energy and industrial sectors producing approximately 43.98 million t, or 22.7% of all GHG in Thailand. The key industries, categorized by IPCC 2006 [4], with very high emissions of GHG are metals and minerals (30%), food and beverages (29%), and petrochemicals (16%) [5]. The petrochemical industry in Thailand is placed in the top 5 the Asian region with a growth rate of 5–12% per year, compared to year 2005 [6]. Moreover, the petrochemical industry is vital to Thai economy, since it spends a lot of investment and operating capital and links with many other industries both within country and overseas. Importantly, this industry is ranked with high proportion of GHG emissions among other industries.

Accordingly, detailed study of GHG emissions from the petrochemical industry will be essential information for creating effective GHG mitigation policies under the Sectoral Approach mechanism in Thailand. Therefore, the research project aims to evaluate the baseline GHG emission and GHG mitigation measures implemented in the Thai petrochemical industry. The project covered the three primary groups of petrochemical producers, including the producers of upstream, intermediate, and downstream petrochemicals. However, this paper presents only the result analysis from the upstream petrochemical industry. The results related to the intermediate and downstream petrochemical industries have been presented elsewhere [7, 8]. The research focuses on identifying sources of GHG emissions and major energy consumption process in the upstream petrochemical production and evaluating the effectiveness of measures to reduce GHG commonly generated in Thai petrochemical plants. This information is essentially helpful for Thailand to set potential GHG reduction targets at an international level and appropriate policy to deal with this issue in the future.

2. PRODUCTION OF UPSTREAM PETROCHEMICAL INDUSTRY

The upstream petrochemical industry has the highest energy consumption comparing with the intermediate and downstream petrochemical industries [9]. The upstream petrochemical products are raw materials for the production of thermoplastics which is the most popular type of plastic groups [10]. As a result, the upstream petrochemical industry becomes a major source of GHG emission. Moreover, trend of GHG emissions is increasing following the higher volume of plastics consumption. The important feedstock for upstream petrochemicals production can be divided into two types: natural gas and naphtha (a by-product of refining crude oil or condensate). Using natural gas as the raw material for petrochemical production can be found in countries which have natural gas resources, like the U.S., Canada and countries in the Middle East. The countries that lack natural gas such as Japan, Korea, and Singapore, normally use naphtha as raw material because of transportation and availability in the global market. Thailand uses both natural gas and naphtha for petrochemical production. In 2007, proportion of feedstock from natural gas was about 25% and about 75% from naphtha.

There are two main processes in the production of upstream petrochemical products. One of them is molecular cracking, a process of cracking large molecules to become smaller ones, which can be divided into two processes, thermal steam cracking and catalytic cracking. In Thailand, most firms mainly implement the thermal steam cracking to produce upstream petrochemical products. Major upstream petrochemical products from this type of process include ethylene, propylene and with mixed C_4, pyrolysis gasoline, methane, hydrogen as by-products. Petrochemical products produced by this process are often classified in the olefins' group. The other is molecular reforming, a process to change molecular structures of hydrocarbons, which may use heat, pressure and/or catalysts combined to get the desired products. This process is often used to change heavy molecules of naphtha into benzene, toluene and xylene, and with hydrogen as a by-product. Petrochemical products produced by this process are often classified in the aromatics' group.

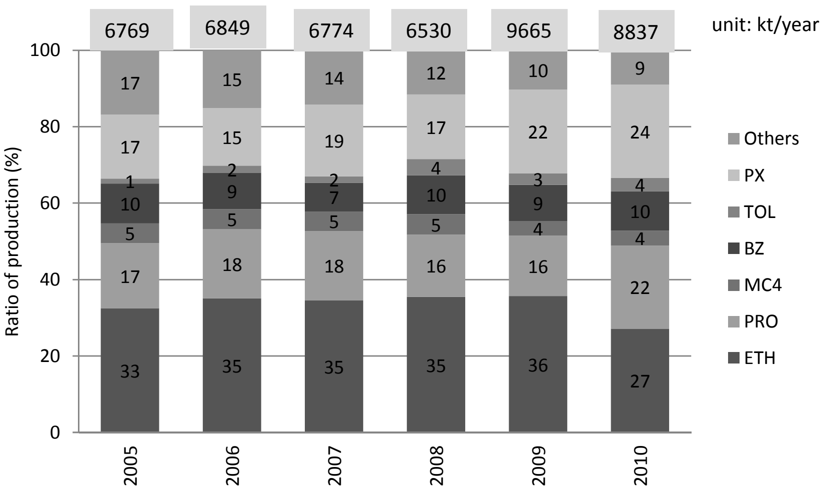

Fig. 1. Productivity of the six representative upstream petrochemical products, [t/year]

Six upstream petrochemical products from both the olefins' group and aromatics' group were chosen as representatives in the research. There are three products from the olefins' group including ethylene (ETH), propylene (PRO) and mixed C_4 (MC_4). Also, three products from the aromatics' group are benzene (BZ), toluene (TOL) and para-xylene (PX). The productivity of upstream petrochemical products during the years 2005–2010 is shown in Fig. 1. The trend of the productivity of both olefins and aromatics is increasing, averaging about 5% per year, with the productivity about 6500–9700 kt/year. In this study, the products and the number of plants for the study were selected using the same criteria with Thai national life cycle inventory database where the capacity of each product must have a total annual production capacity of more than 60% of the total quantity of production in the upstream petrochemical industry. As shown in Figure 1, the total productivity of the six representative products selected for this study is about 85% of total productivity, which is consistent with the mentioned criteria. Total productivity of the six representative products is between 5600–8700 kt/year. Total productivity from the olefins' group is approximately 55% and aromatics' group is approximately 30%. Products in the olefins' group with the highest productivity are ETH, followed by PRO and MC_4, respectively. Products in the aromatics' group with the highest productivity are PX, followed by BZ and TOL, respectively.

3. METHOD

3.1. SYSTEM BOUNDARIES AND GHG ACCOUNTING

Seven upstream petrochemical plants participated to provide relevant information for primary and secondary data and the total productivity of upstream petrochemical production. Seven upstream petrochemical plants together produce about 85% of volume of upstream petrochemical products in Thailand. Duration for GHG emission evaluation covered the years 2005–2010. This study determined boundary of GHG emissions, following the GHG Protocol [11] which divides the emissions of GHG into the two following scopes.

Scope 1. Direct GHG emission considered from the production process including fuel combustion, flare and process vent referred to the *IPCC 2006 Guidelines for National GHG Inventories*, Volume 3. *Industrial Process and Product Use* [3] as shown in Eqs. (1), (2).

$$E_{\text{Direct}} = E_{\text{Combustion}} + E_{\text{Process vent}} + E_{\text{Flare}} \tag{1}$$

where E_{Direct} is the GHG emission from the direct GHG emission (t GHG), $E_{\text{Combustion}}$ – GHG emitted from the fuel combusted to provide heat (t GHG), $E_{\text{Process vent}}$ – GHG emitted from the process vent (t GHG) which has very little GHG emission being neglected in this study, E_{Flare}= GHG emitted from the flare gas (t GHG)

$$E_{\text{Combustion}}(E_{\text{Flare}}) = \sum \left(FA_k \times NCV_k \times EF_k \right) \tag{2}$$

where FA_k is the amount of fuel k or flare gas k consumed for production (t), NCV_k – net calorific value of fuel k or flare gas k (TJ/t), EF_k – emission factor of fuel k or flare gas k (t GHG/TJ). For GHG emission factors used to calculate the amount of GHG emissions were collected from industries.

Scope 2. Use of indirect GHG emission originating from the purchase of electricity and steam in the production:

$$E_{\text{Indirect}} = (\text{Activity data}) \times EF \tag{3}$$

where E_{Indirect} is the GHG emission from indirect GHG (t GHG), activity data – amount of electricity consumption or steam consumption, EF = emission factor of electricity or steam (t GHG/unit), for GHG emission factors used to calculate the amount of GHG emissions was obtained from sources of purchased electricity and steam.

In this research, input/output inventory data has been collected from production processes in all of the seven petrochemical plants (covering 6 products) during the years 2005–2010, and used this information to evaluate GHG emissions under the model of IPCC 2007 [12]. The scope set forth includes direct and indirect GHG emissions, with direct GHG emissions sources being energy used as the combustion of fuel (fuel), energy used from the combustion of fuel which is a by-product of the production process (fuel byproduct) and burning flares (flares). Sources of indirect GHG emissions include the electricity and steam purchased from outside the plant (electricity, steam). The GHG being examined include CO_2, CH_4 and N_2O. Total sum of these three gasses is calculated in units of carbon dioxide equivalent, using the global warming potential value (GWP) according to IPCC 2007:

$$CO_{2\,\text{eq}} = (\text{GHG emission}) \times GWP \tag{4}$$

where $CO_{2\,\text{eq}}$ is the amount of GHG in term of tons of carbon dioxide equivalent (t $CO_{2\,\text{eq}}$), the GHG emission is calculated from direct GHG emission and indirect GHG emission (t GHG), GWP – global warming potential (t $CO_{2\,\text{eq}}$/t GHG).

The total GHG emissions of each petrochemical plants n will be calculated from:

$$E_n = E_{\text{direct},\,n} + E_{\text{indirect},\,n} \tag{5}$$

where E_n is the total GHG emission of plant n (t $CO_{2\,\text{eq}}$).

The results of evaluation of GHG emission from petrochemical products are presented as carbon intensity (*CI*). In this research, also energy intensity (*EI*) and the amount of energy used in production has been defined:

$$CI_j = \frac{\sum_n E_{n,j}}{\sum_n P_{n,j}} \tag{6}$$

$$EI_j = \frac{\sum_n EC_{n,j}}{\sum_n P_{n,j}} \tag{7}$$

CI_j is the carbon intensity of representative product j (t $CO_{2\ eq}$/t product), EI_j – energy intensity of representative product j (MJ/t product), $E_{n,j}$ – total GHG emission of plant n which produced product j (t $CO_{2\ eq}$), $EC_{n,j}$ – total energy consumption of plant n which produced product j (MJ), $P_{n,j}$ – amount of production of plant n which produced product j (t product).

3.2. ENERGY CONSERVATION MEASURES FOR REDUCING GHG

By collecting data of energy conservation measures during the 2005–2010 period, the reduction of carbon intensity and reduction of energy intensity of each measure were calculated:

$$CI_{re,j} = \frac{\sum_n E_{re,n,j}}{\sum_n P_{n,j}} \tag{8}$$

$$EI_{re,j} \frac{\sum_n EC_{re,n,j}}{\sum_n P_{n,j}} \tag{9}$$

$CI_{re,j}$ is the carbon intensity reduction by using measure j (t $CO_{2\ eq}$/t product), $EI_{re,j}$ – energy intensity reduction by using measure j (MJ/t product), $E_{re,n,j}$ = GHG reduction of plant *n* by using measure *j* (t $CO_{2\ eq}$), $EC_{re,n,j}$ – energy reduction of plant *n* by using measure *j* (MJ), $P_{n,j}$ – amount of production of plant *n* which used measure *j* (t product).

3.3. GHG EMISSION FORECAST FROM UPSTREAM PETROCHEMICAL SECTOR

To estimate the energy consumption and GHG emissions within all groups of the petrochemical industry, the forecast has been made to forecast the total production from upstream sectors using the proportion of the representative products and the production in the entire country. The assumption is that petrochemical products have a similar level of energy consumption and GHG emission based on the current level of technology and same energy consumption rate. The forecast of the GHG emission of the country followed the equations:

$$E_j = CI_j P_j \tag{10}$$

$$E_t = \frac{P_i}{\sum_j P_j} \sum_j E_j \tag{11}$$

$$EC_j = EI_j P_j \tag{12}$$

$$EC_t = \frac{P_t}{\sum_j P_j} \sum_j EC_j \tag{13}$$

E_j – total GHG emission of product *j* (t $CO_{2\ eq}$), E_t – total GHG emission of upstream petrochemical industry (t $CO_{2\ eq}$), EC_j – total energy consumption of product *j* (t $CO_{2\ eq}$), EC_t – total energy consumption of upstream petrochemical industry (t $CO_{2\ eq}$), CI_j – carbon intensity of product *j* (t $CO_{2\ eq}$/t product), EI_j – energy intensity of product *j* (t $CO_{2\ eq}$/t product), P_j – productivity of product *j* (t product), P_t – productivity of upstream petrochemical industry (t product).

4. RESULTS AND DISCUSSION

4.1. ENERGY INTENSITY AND CARBON INTENSITY

The average energy intensity (*EI*) of upstream petrochemical products during the years 2005–2010 was evaluated as shown in Fig. 2. The olefins' group has a higher *EI* value than that for the aromatics' group. This may be caused by the olefins using heat to crack molecules of raw materials to make a product while the aromatics' groups only use heat to distil and separate their product. The product with the highest *EI* is mixed C_4 with 23 588 MJ/t and the product with the minimum average *EI* is benzene with 7189 MJ/t, almost 3 times lower. The *EI* values of the olefins and aromatics in the years 2005–2010 range from 21 080 to 24 041 and 6611 and 12 334 MJ/t, respectively. The trends in *EI* during the period 2005–2010 have likely to decline about 30% of the *EI* value in 2005 due to most plants taking energy conservation measures within their industrial manufacturing processes according to the Royal Thai Government's Promotion of Energy Conservation Act, resulting in more efficient energy usage.

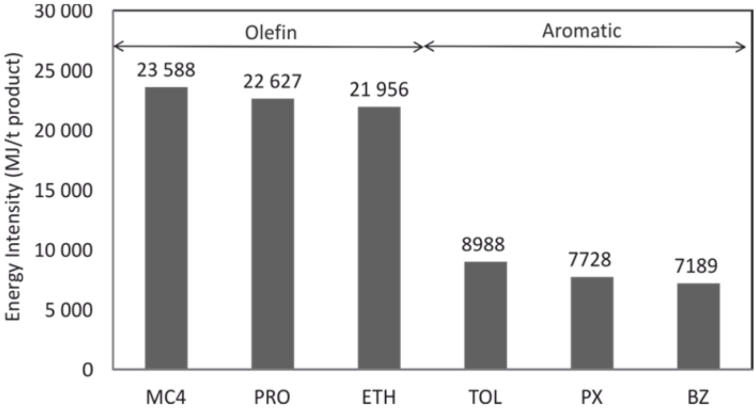

Fig. 2. Average energy intensity of upstream petrochemical products during 2005–2010

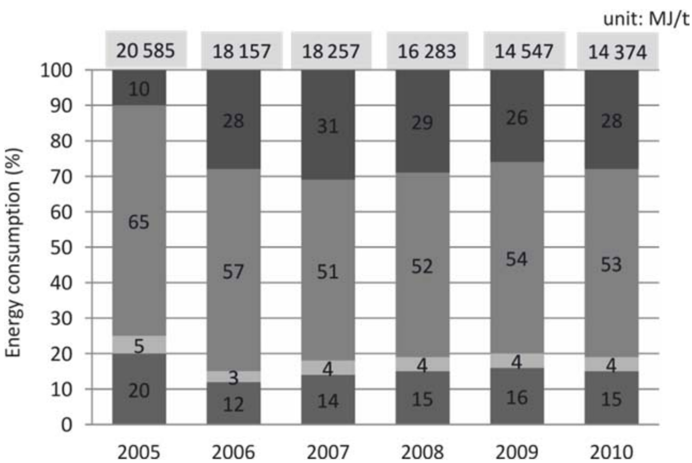

Fig. 3. Ratio of energy consumption separated by energy source during 2005–2010

Proportion of energy consumption in the upstream petrochemical production between the years 2005 and 2010 is shown in Fig. 3. Energy consumption was analyzed according to the source of energy, including direct energy (fuel, fuel by-product) and indirect energy (electricity and steam). The direct energy consumption for upstream petrochemical production is higher than the indirect one ca. 4 times, as a portion of 80% and 20%, respectively. The direct energy used in the process of molecular cracking in the olefins' group, which is a process that requires much heat to break down complex organic molecules into simpler ones by breaking carbon–carbon bonds in the precursors. For the aromatics' group of products, direct energy is used in the process of reforming hydrocarbons. This is a process that uses much heat and high pressure with a catalyst to change the molecules of heavy naphtha into the groups of aromatics.

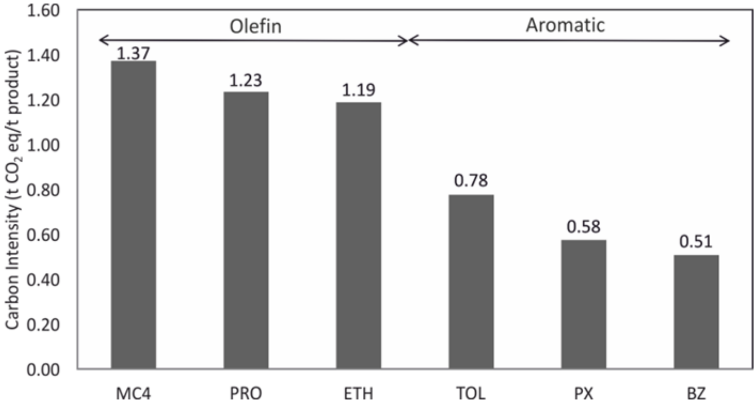

Fig. 4. Average carbon intensity of upstream petrochemical products during 2005–2010

Average *CI* of upstream petrochemical products during 2005–2010 is analyzed as shown in Fig. 4. From the average *CI* of upstream petrochemical products was approximately 0.94 t CO_{2eq}/t product. The olefins have higher *CI* than that of the aromatics, which corresponds with the *EI* values mentioned above. The upstream product with the highest *CI* is mixed C_4, with an average of 1.37 t CO_{2eq}/t and the product with the lowest *CI* is benzene with an average of 0.51 t CO_{2eq}/t.

The raw materials used in the production of olefins in Thailand are natural gas based raw materials, including ethane, propane, LPG and liquid based including, naphtha, NGL and raffinate. The sources of GHG in the production of olefins come from fuel combustion to heat and cause the molecules of the raw materials to crack with steam in cracking furnaces. The fuels burned include not only natural gas and coal but also methane and hydrogen, which are by-products in the production process of molecular cracking. Additionally, there are also sources of GHG from other processes. These include the elimination of CO_2 from ethane when used as a raw material, the removal of coal dregs in the chimneys, and the burning of excess fuel or non-standard products.

The values of *CI* of olefins and aromatics in the years 2005–2010 range between 1.13 and 1.31 or 0.52 and 0.67 t CO_{2eq}/t, respectively. When comparing this *CI* value with Europe, 1.9 t CO_{2eq}/t, it was found that the *CI* of the olefins products in Europe are higher those in Thailand by approximately 40%, as Europe mainly uses naphtha and gas oil as feedstock in the production of olefins [13], while Thailand uses natural gas as a feedstock. The trend of the *CI* of the olefins and aromatics during the years 2005–2010 decreased steadily in parallel with trend in the *EI* values because most plants in the upstream petrochemical industry had implemented energy conservation measures and had better improved energy efficiency in their manufacturing processes. This resulted in the *EI* and *CI* from the production process to decrease accordingly. By the year 2010, the *CI* of upstream petrochemical products reduced by about 34% from the year 2005.

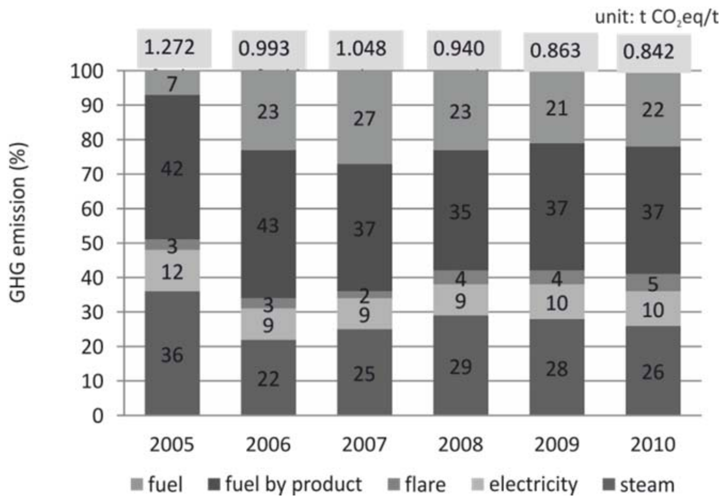

Fig. 5. Ratio of GHG emission separated by GHG emission source during 2005–2010

The average values of the major sources of GHG in the upstream petrochemical productions during the years 2005–2010 were analyzed as shown in Fig. 5. The important sources of GHG in the upstream production are the fuel by-product, steam, fuel, electricity and flares in respective order. The proportion of GHG emissions is 39, 28, 20, 10 and 3%, respectively. The direct GHG emissions (fuel, fuel by-product, flare) have a higher value of GHG emissions than indirect (electricity and steam) by about 1.6 times, or as a proportion of 62% and 38%, respectively.

4.2. COMPARISON OF ENERGY AND CARBON INTENSITIES WITH BAT AND BPT

Estimated energy intensities (*EI*) and carbon intensities (*CI*) of Thai petrochemical products have been summarized in Table 1 and compared them to the corresponding values for other countries worldwide based on the reported data after implementing Best Available Technology (BAT) [14] and Best Practice Technology (BPT) by IEA [15].

Table 1

Summary of energy and carbon intensity for the petrochemical industry

Product	Energy intensity [GJ/t]			Carbon intensity [t CO_2 eq/t]	
	BAT [14]	BPT [15]	This study (2005–2010)	(2004) [13]	This study (2005–2010)
Upstream					
Ethylene	13.00	12.00	21.956*	1.73–2.45	1.19
Propylene	13.52	12.00	22.627*		1.23
p-Xylene	7.30		7.728	0.69	0.58
Toluene	2.10		8.988		0.78
Benzene	12.00		7.189	0.84	0.51

Energy from feedstock not included.

The *EI* from Thai petrochemical products majority are slightly higher than those from other countries. However, a few types of the Thai products have lower *EI* than in other countries such asp-xylene and benzene. Therefore, Thailand still has high potentials in GHG reduction by reducing energy consumption with BAT/BPT including electricity and heat generation with CHP system, electricity conservation measures, production process renovation. The improvement will also provide cost-saving on energy expenses. Meanwhile, average *CI* of Thai petrochemical products have relatively similar or lower than that found in other countries. These may cause by the uses of natural gases as sources of energy and raw materials.

4.3. PROJECTION OF ENERGY CONSUMPTION AND GHG EMISSIONS FROM THE UPSTREAM PETROCHEMICAL INDUSTRY

Total energy consumption of the entire petrochemical industry during 2005–2010 is summarized in Fig. 6. Total energy consumption ranges from 110 000 to 150 000 TJ, where the olefin and aromatic products have proportions of 73 and 14%, respectively. The data from energy report of Thailand shows that in the years 2007–2010 Thailand's energy consumption was at 65 500–71 000 KTOE or about 2 700 000–3 000 000 TJ [16]. Therefore, the energy consumption of the upstream petrochemical industry accounted for 5–6% of the total energy consumption in the country. The olefins product group (ETH, PRO, MC_4) have the energy use about five times higher than the aromatics product group (BZ, TOL, PX).Ethylene is a product in the olefins' group with the highest energy consumption, accounting for 43% of the energy consumption of the entire upstream petrochemical industry group. This is followed by PRO, PX, MC4, BZ, TOL, which account for 24, 8, 6, 4 and 1%, respectively. When considering the overall energy consumption of the petrochemical industry, the amount of energy consumption increases steadily by about 5% per year following the production of upstream petrochemical products that increases every year.

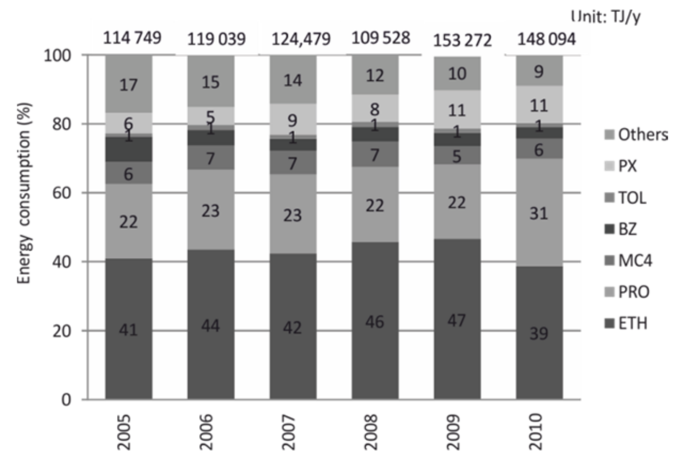

Fig. 6. Energy consumption of Thailand upstream petrochemical industry during 2005–2010

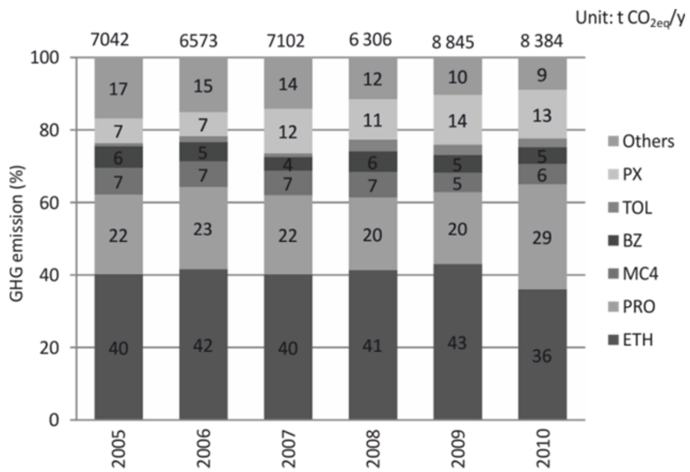

Fig. 7. GHG emission of Thailand upstream petrochemical industry during 2005–2010

The amount of GHG emissions from the Thai upstream petrochemical industry during 2005–2010 is summarized in Fig. 7. Total GHG emission from this sector is approximately 7000–9000 t $CO_{2\ eq}$/year, from the olefins' and aromatics' products with proportions of around 69% and 18%, respectively. The olefins' product group (ETH, PRO, MC_4) have an amount of GHG emissions about four times higher than the aromatics' product group (BZ, TOL, PX) due to the production capacity and the demand for energy of the olefins' product group being about 2 times higher than the aromatics' group, impacting the amount of GHG emissions being more as well. Ethylene is the product in the olefins' group with the highest amount of GHG emissions with its proportion of GHG emissions being about 40% of the total GHG emissions from the upstream petrochemical industry, followed by PRO, PX, MC4, BZ, TOL, with proportions of 22, 11, 7, 5, and 2% , respectively. When considering the overall GHG emissions of the upstream petrochemical industry, the amount of GHG emissions increases steadily by about 3% per year with the lowest value of GHG emissions in 2005, equal to 7042 kt CO_{2eq} and the highest value in 2010, equal to 8384 kt $CO_{2\ eq}$. However, due to the global economic slowdown in 2008, the production capacity of all products dramatically reduced, which is an important factor that contributed to the reduction of GHG emissions. When the economic factors returned to normal in the years 2009–2010, manufacturers in the petrochemical industry expanded their capacity to accommodate the increase in the rate of market demand, both domestically and internationally, resulting in the volume of GHG emissions increasing steadily, with the rate increasing 35% from 2008. Data from WRI, 2008 [17] and CDIAC, 2009 [18] identified that Thailand had GHG emissions in the years 2005–2006 ranging between 375–425 Mt $CO_{2\ eq}$, while evaluation of the amount of GHG emissions from the upstream petrochemical industry in the same year revealed that the amount of GHG was about 6.5–7 Mt $CO_{2\ eq}$, which as a proportion was 2% of the entire country's GHG emissions.

4.4. GHG REDUCTION AND ENERGY CONSERVATION MEASURES WITHIN REPRESENTATIVE FACTORIES

Analysis of energy conservation measures within representative upstream petrochemical factories is shown in Table 2. The measures are divided into three groups including energy saving measures, steam saving measures and fuel saving measures. In Table 2, the details are given of each measure that factories implemented to save or reduce amount of energy consumption and amount of energy saved after implementation each measure. Efficiency of each measure for energy conservation is very informative for any firm to decide whether to implement in the future. The reductions of *EI* and *CI* from the entire sector were estimated and after implementation energy conservation measure help to reduce *EI* and *CI* by about 1700 MJ/t and 0.20 t $CO_{2\ eq}$/t, representing a decrease of approximately 9 and 16%, respectively, from the average intensity in 2005. The fuel saving measures reduced the most *EI* and *CI* intensities, followed by steam and electricity saving measures.

Table 2

The energy conservation measures from representative upstream petrochemical plants

Energy conservation approaches		*EI* reduction		*CI* reduction	
		[MJ/t]	[%]	[t CO_2 eq/t]	[%]
Electricity saving	Reducing energy consumption of equipment (e.g. air compressor, impeller, propeller)	1.15×10^{1}	0.67	1.76^{-3}	0.97
	Controlling the proportion of hydrogen/hydrocarbon	7.07×10	0.41	1.08^{-3}	0.59
	Changing the air condition to split type	5.47×10^{-1}	0.03	6.38×10^{-5}	0.04
	Reducing energy consumption in ethylene input/output system	4.04×10^{-1}	0.02	4.72×10^{-5}	0.03
	Reducing the use of water pumps at low production capacity	1.74×10^{-1}	0.01	2.66×10^{-5}	0.01
	Others	9.55×10^{-2}	0.01	6.84×10^{-4}	0.38
	Sub-total	1.98×10^{1}	1.15	3.66×10^{-3}	2.01
Steam saving	Heat recovery from boiler	9.15×10^{1}	5.30	3.18×10^{-2}	17.47
	Reducing steam consumption	8.09×10^{1}	4.68	1.26×10^{-2}	6.92
	Reducing heat loss from steam trap	6.27×10^{1}	3.63	9.47×10^{-4}	0.52
	Sub-total	2.35×10^{2}	13.61	4.53×10^{-2}	24.91
Fuel saving	Controlling excess oxygen of cracking furnace	4.41×10^{2}	25.53	2.80×10^{-2}	15.38
	Maintaining the tools and equipment for longer life	3.27×10^{2}	18.93	2.09×10^{-2}	11.48
	Improving furnace efficiency such as heat exchange system	1.89×10^{2}	10.94	1.20×10^{-2}	6.59
	Increasing the temperature at the bottom tower of quench oil system	1.04×10^{2}	6.02	1.62×10^{-2}	8.90
	Controlling the fuel distribution system of cracking furnace	1.02×10^{2}	5.91	1.52×10^{-2}	8.35
	Others	3.09×10^{2}	17.91	4.08×10^{-2}	22.39
	Sub-total	1.47×10^{3}	85.24	1.33×10^{-1}	73.08
Total		1.73×10^{3}	100.00	1.82×10^{-1}	100.00

The proportion of *EI* and *CI* that reduced from the fuel, steam and electricity saving measures had proportions of 84%, 13% and 3%, and, 67%, 23% and 10%, respectively. Evidently, the fuel saving measures was the main measures to reduce energy consumption and reduce GHG emissions in the upstream petrochemical industry. This probably is because the main production process used fuel combustion to generate heat in the molecular cracking and reforming processes. In the group of fuel saving measures, the best reduction of *EI* and *CI* measure is reduction of excess air in the cracking furnace, which was able to reduce the *EI* and *CI* by 25 and 14%, respectively.

The measure in the group of steam saving that has the most *EI* and *CI* reduction is heat recovery for use in the water boiler (waste heat boiler), which was able to reduce the intensities by 5 and 16%, respectively.

5. CONCLUSIONS

In the research, the amount and sources of GHG emissions in the Thai upstream petrochemical industry during the 2005–2010 period have been analyzed. Moreover, the study also evaluated potential for reducing GHG from each of the energy conservation measures used in the petrochemical industry. The average values of *CI* of upstream petrochemical products were approximately 0.94 t CO_{2eq}/t, and the *CI* of the olefins was higher than that of the aromatics. The *CI* of olefins and aromatics in the years 2005–2010 ranged between 1.13–1.31 and 0.52–0.67 t CO_{2eq}/t, respectively. The upstream product with the highest *CI* is MC_4, followed by PRO, ETH, TOL, PX and BZ. This is consistent with the *EI* values. The *EI* of olefins and aromatics in the years 2005–2010 ranged between 21 080–24 041 and 6611–12 334 MJ/t, respectively. The largest source of GHG emissions from the upstream petrochemical industry (80%) came from the direct combustion of fuel in the process of molecular cracking, for the olefins' products group, and the process of molecular structure reforming of hydrocarbons for the aromatic products group.

Regarding the potential for different GHG reduction measures, it was found that the fuel saving measures (reducing direct energy) have the highest potential to reduce GHG emissions from the upstream petrochemical industries. In the group of fuel saving measures, the reduction of excess air in the cracking furnace had the best reduction of *EI* (4.41×10^2 MJ/t) and *CI* (2.80×10^{-2} t $CO_{2\ eq}$/t). These results provide important information for planning to reduce GHG emissions in the petrochemical industry in the future by taking into account the proportion of GHG emissions from each different source and the potential measures for reducing GHG emissions with each different options as well.

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