Energy for Sustainable Development 34 (2016) 88–99

Contents lists available at ScienceDirect

Energy for Sustainable Development

Energy, environmental, and economic analysis of energy conservation measures in Thailand's upstream petrochemical industry

Thanapol Tantisattayakul [a,*], Chanathip Pharino [b,c], Orathai Chavalparit [b,c], Premrudee Kanchanapiya [d]

[a] Faculty of Science and Technology, Thammasat University, Thailand
[b] Department of Environmental Engineering, Faculty of Engineering, Chulalongkorn University, Thailand
[c] Research unit of Environmental Management and Sustainable Industry, Faculty of Engineering, Chulalongkorn University, Bangkok, Thailand
[d] National Metal and Materials Technology Center(MTEC), National Science and Technology Development Agency(NSTDA), Pathumthani, Thailand

ARTICLE INFO

Article history:
Received 12 November 2014
Revised 16 July 2016
Accepted 17 July 2016
Available online xxxx

Keywords:
Energy conservation
Energy saving potential
Emission reduction potential
Upstream petrochemical industry

ABSTRACT

Upstream petrochemical industry accounts for the highest energy consumption among all stages of petrochemical industry in Thailand. The energy conservation in this industry is essential for sustainable industrial development. In this research, the performance of energy conservation measures adopted in Thailand's upstream petrochemical industry are in-depth analyzed in energy, environmental, and economic cost effectiveness perspectives by using four indices: (1) reduction in energy intensity (EnRI), (2) reduction in carbon intensity (ERI), (3) energy consumption reduction on investment (EnROI), and (4) greenhouse gas (GHG) emission reduction on investment (EROI). Furthermore, the methods for evaluating the economic feasibility, and estimating the potential for energy saving and GHG emission reduction are proposed. The analyzed result suggests that the energy saving and greenhouse gas emission reduction potential are 5,267 GJ/million USD of product and 450 tCO_{2eq}/million USD of product, and 5,272 GJ/million USD of product and 451 tCO_{2eq}/million USD of product, in case of without and with carbon credit, respectively. The evaluation and assessment method proposed in this research can support decision makers to analyze and evaluate the economic feasibility of the measures under various policies and pricing scenarios of energy and carbon credit and, can be applied in other industries as well.

Introduction

The world is currently faced with the problem of climate change, which is finally causing wide impacts on both human and global environments. Greenhouse gas emissions from human activities, especially energy use, are the most significant cause of these problems. In 2013, Thailand had a total final energy consumption of 75,214 ktoe. The industrial sector was the highest energy consuming sector, accounting for 36.2% of the total final energy consumption and emitting 21% of the total greenhouse gases (DEDE, 2013). Within the industrial sector, the petrochemical industry was responsible for 23% of the total emissions of the sector (Kanchanapiya et al., 2014).

The petrochemical industry has a significant effect on the development of the country both directly and indirectly. Not only does it add value to oil and natural gas, but it is also related to numerous other industries, such as packaging, spare parts, electronic parts, textile, and construction. The petrochemical industry can be divided into three stages: (1) upstream, (2) intermediate and (3) downstream. The upstream stage transforms petroleum products, such as ethane, propane, liquefied petroleum gas (LPG), natural gasoline (NGL) and condensate or oil products as naphtha, into raw materials (olefin and aromatic) for derivative petrochemicals production. The intermediate stage uses petrochemicals produced by the upstream industry to produce petrochemical products that are further used as raw materials by the downstream industry. The downstream stage uses upstream or intermediate products as feedstock to produce downstream petrochemicals such as plastic resins or synthetic materials, which are feedstock for related industries. There are two main processes in the production of upstream petrochemical products. The first is the molecular cracking process, a process of cracking the large molecules into smaller molecules, which can in turn 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 mixed C4, with methane and hydrogen as by-products. Petrochemical products produced by this process are classified in the olefin group. The second process is molecular reforming process, a process to change the molecular structure of hydrocarbons, which may use heat, pressure and/or a catalyst to obtain the desired products. This process is often used to change the heavy

* Corresponding author at: Faculty of Science and Technology, Thammasat University, 12121, Thailand.
E-mail address: thanapolosk@hotmail.com (T. Tantisattayakul).

http://dx.doi.org/10.1016/j.esd.2016.07.006
0973-0826/

molecules of naphtha into benzene, toluene and xylene, with hydrogen as a by-product. The petrochemical products produced by this process are classified in the aromatic group. These two major categories, olefin and aromatic, have a total production capacity of 8,309,000 tons/yr (PITI, 2011). The upstream petrochemical industry is the industry that has the highest energy consumption compared to the intermediate and downstream petrochemical industries (DEDE, 2007). The amount of GHG emissions from the petrochemical industry during 2005–2010 was approximately 8000 to 12,000 kt CO_2 eq./year. This value represents approximately 3% of the total GHG emissions of Thailand. The upstream petrochemical industry accounted for the highest GHG emissions at 62%, whereas the intermediate and downstream groups were responsible for 21% and 17%, respectively (Kanchanapiya et al., 2014). Therefore, energy conservation has become an important issue to improve energy efficiency and reduce GHG emissions. Energy conservation measures (ECMs) need to be applied to improve energy efficiency, taking into account environmental impacts and energy security.

Energy conservation in the petrochemical industry was studied by various researchers including Neelis et al. (2008), who conducted a study on ECMs employed in the U.S. petrochemical industry and found a number of implemented measures, for example, combined heat and power (CHP) measures, steam trap improvement measures, furnace efficiency improvement measures, waste heat recovery measures, pump size and efficiency improvement measures, condensate recovery measures and measures for adjusting propeller speed. Lu et al. (2013) conducted a study on methods with potential for greenhouse gas emissions reduction due to energy consumption of the petrochemical industry in Taiwan in line with the best practice technology and found the efficient methods for reducing greenhouse gas emissions to be reducing heat consumption through heat recovery, cogeneration or combined heat and power, reducing electricity use and improving the production process. Lee (2013) conducted a study on existing and anticipated technology strategies for reducing greenhouse gas emissions in Korea's petrochemical and steel industries and found that the measures regarding energy saving and process innovation are the most widely adopted and implemented technology options for reducing GHG emissions and that the measures regarding energy source and raw materials substitution are expected to emerge within 5–10 years. Mohammadi et al. (2013) conducted a study on the energy efficiency measures employed in the Iranian petrochemical industry and found the measures to be divided into seven systems: steam systems, furnaces and process heating systems, heating–cooling and process integration systems, motor systems, pump systems, compressors and compressed air systems and distillation systems. Tian et al. (2012) conducted a study on energy saving potential in a Chinese fine chemical industrial park and found that the following five types of energy-saving technical measures were most promising: 1)application of variable frequency technology; 2) using efficient steam-consuming dryers; 3) using energy-efficient refrigerators; 4)recovery of steam condensate, and 5) improving the power factor of transformers. Neelis et al. (2007) approximated the theoretical energy saving potentials for the petrochemical industry using energy balances in 68 key processes in Western Europe and estimated the energy loss in Western Europe to be 1936 PJ, resulting in a total of 127 Mt CO_{2e}. In Thailand, Charmondusit and Keartpakpraek (2011) conducted an eco-efficiency evaluation of the 31 factories in the petroleum and petrochemical group and found that the upstream factories were the highest in material and water consumption and in hazardous waste generation but did not report information related to the energy aspect due to limited data.

The objective of this research is to perform an in-depth evaluation of the ECMs implemented in Thai upstream petrochemical industry in the energy (energy consumption reduction), environmental (GHG emissions reduction) and economic (cost-effectiveness) perspectives. This research also proposes indices and method to assess the performance of the ECMs and estimate the energy saving and emission reduction potential resulting from the ECMs.

Methodology

System and energy conservation measures scope

There are a total of eight upstream petrochemical plants in Thailand. For this research, data were obtained from four sample factories covering six products that could be divided into two groups: olefin (such as ethylene, propylene, mix C4) and aromatic (such as benzene, toluene, xylene). The production capacity for the sample olefin plants is 2739 kton/yr, or 64% of the nation's total capacity, and the capacity for the sample aromatic plants is 2028 kton/yr, or 55% of the nation's total capacity, as described in Table 1.

In evaluating GHG reduction, the data of the ECMs during 2010–2012 were gathered and summarized from the energy management reports including data regarding the total annual energy use, the ECMs implemented, and the energy savings. To calculate the GHG emission reductions resulting from the ECMs, the calculation methods of the CDM approved methodologies were applied as standard calculation methods. According to the findings, a total of 18 ECMs were implemented in the sample plants, which can be grouped and categorized into the following five categories: 1) steam saving and steam loss reduction (SS), 2) steam optimization (SO), 3) cogeneration (CO), 4) energy efficiency (EE), and 5) waste energy recovery (WE). The CDM methodologies corresponding to the categories of the measures described above are AM0017, AM0018, AM0048, AMS.II.C, and AMS.III.Q, respectively, as shown in Table 2.

The steam saving and steam loss reduction (SS) is a category of measures that reduces steam loss from steam traps and/or return condensate to a boiler to increase the energy efficiency of a steam system. The steam optimization (SO) is a category of measures that optimizes the steam distribution or improves the efficiency of the steam system used in the production process, further reducing steam consumption, reducing fossil fuel consumption in the steam boiler, and consequently reducing GHG emissions. The cogeneration (CO) is a category of measures that installs a new cogeneration system to replacing the previous systems using thermal energy in steam and electrical power from other sources, which helps cut fuel consumption. The energy efficiency (EE) is a category of measures that improves the energy efficiency of equipment in the production process, resulting in electrical power or fuel saving, which consequently reduces fossil fuel consumption and GHG emissions. The waste energy recovery (WE) is a category of measures that recovers the waste energy and uses it as source of electrical power, mechanical power and heat, which helps reduce fossil fuel consumption.

Assessment of energy saving and emission reduction

The assessment of the energy saving from the ECMs covered energy from direct fuel combustion in plants as well as thermal energy

Table 1
Production data of the representative upstream petrochemical products.

Type	Product value (USD/ton of product)	Production capacity (kton/yr)		Representative factory/all factories (%)
		Representative factory	All factories	
Olefin	1352	2739	4251	64
Aromatic	557	2028	3706	55

Table 2
CDM methodologies considered for energy conservation measures in this research.

Category of measure	Calculation method of GHG emission and energy saving	References
Steam saving and steam loss reduction (SS)	AM0017 Steam system efficiency improvements by replacing steam traps and returning condensate	UNFCCC (2005)
Steam optimization (SO)	AM0018 Baseline methodology for steam optimization systems	UNFCCC (2012a)
Cogeneration (CO)	AM0048 New cogeneration facilities supplying electricity and/or steam	UNFCCC (2010)
Energy efficiency (electrical and thermal) (EE)	AMS.II.C Demand-side energy efficiency activities for specific technologies	UNFCCC (2012b)
Waste energy recovery (WE)	AMS.III.Q Waste energy recovery (gas/heat/pressure) projects	UNFCCC (2012c)

in steam and electrical power purchased from outside of the plants. The energy consumption reduction of each measure are calculated by Eq. (1).

$$EnR = BEn - PEn \tag{1}$$

where:

EnR Energy consumption reduction (TJ/year)
PEn Project energy consumption (TJ/year)
BEn Baseline energy consumption (TJ/year)

The PEn and BEn are the energy consumption after implementing the ECM and the energy that would be consumed by the exiting process in the absence of the ECM, respectively. They were calculated in line with the CDM methodologies, using the information regarding amount and types of energy used, and production data in the energy management reports obtained from the sample plants. The detail of the parameters and calculation method can be consulted with the references listed in Table 2.

To compare the energy saving among different measures and products, the reduction in energy consumption intensity (EnRI) (TJ/USD), as shown in Eq. (2), is proposed.

$$EnRI = \frac{EnR}{price \times C} \tag{2}$$

where:

$EnRI$ Reduction in energy intensity (TJ/USD)
EnR Energy consumption reduction (TJ/year)
$price$ Market price of product (USD/ton of product)
C Annual production of product (ton of product/year)

The EnRI is defined as the proportion between the energy consumption reductions and the value of product produced in the factory in which the measure was adopted. It is a normalized form of energy saving by amount of product. The reason for using the product value instead of the tons of the product as the denominator is to obtain comparable values between different products (olefin and aromatic) in the same sector. The product value reflects the production cost that implies the size of factory in which the products are produced as well as the facilities and their energy use. The market prices of products (olefin and aromatic) applied in this research were the average price of year 2010 obtained from petroleum institute of Thailand (PITI, 2011) and were set as a constant value to eliminate fluctuation in price during the considered period (2010–2012). This index indicates energy benefit in terms of how much energy intensity of the factory can be reduced from implementing the ECM. A high value means that the measure has the energy benefit higher than those of a low value in the same sector. Moreover, this index can be used to estimate the energy that could be reduced per product value from implementing the measure being considered.

The value calculated by Eq. (2) is the EnRI of each ECM. To compare the aggregate EnRI for each product and each measure category, the average EnRI for the product and measure category can be calculated, as shown in Eq. (3):

$$EnRI_{PM} = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} EnR_{i,j,M}}{\sum_{i=1}^{m}(price_P \times C_{i,P})} \tag{3}$$

where:

$EnRI_{PM}$ Average reduction in energy intensity of product P (olefin and aromatic) due to ECMs under category M
$EnR_{i,j,M}$ Energy consumption reduction in factory i due to ECM j under category M (TJ/year)
$price_P$ Market price of product P (USD/Ton of product P)
$C_{i,P}$ Annual production of product P in factory i (Ton of product P/year)
n Number of ECMs under category M in factory i
m Number of factories producing product P
i Index number of factories producing product P
j Index number of ECMs under category M
P Petrochemical products
M Category of ECMs

Assessment of the GHG emission reduction

The GHG emission reduction from ECMs was assessed using the CDM's calculation method. The assessment covered sources of direct and indirect GHG emissions. Direct sources for GHG emissions are from energy consumption due to the combustion of fuel within the plants, and indirect sources are the thermal energy in steam and the electrical power purchased from outside of the plants. The GHG taken into account includes three types of gases, namely, CO_2, CH_4 and N_2O. In the assessment of GHG emission reduction, the total of the three types of gases is calculated in units of carbon dioxide equivalent (tCO_{2eq}) using the Global Warming Potential (GWP) values according to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2016). The calculation results for each ECM are presented in the GHG emission reduction (tCO_{2eq}/year), as shown in Eq. (4). To compare the GHG emission reductions among products (olefin and aromatic) and factories, the reduction in carbon intensity (ERI) (tCO_{2eq}/USD), as shown in Eq. (5), was calculated. The ERI is the GHG reduction normalized by the product value similar to the EnRI introduced in Assessment of energy saving and emission reduction section.

$$ER = BE - PE \tag{4}$$

where

ER GHG emission reduction (tCO_{2eq}/year)
PE Project GHG emission (tCO_{2eq}/year)
BE Baseline GHG emission (tCO_{2eq}/year)

The PE and BE are the GHG emission after implementing the ECM and the GHG that would be emitted by the exiting process in the absence of the ECM, respectively. They were calculated by using the information regarding the amount and types of energy used before and after implementing the measure and emission factor of the energy source. The detail of the parameters and calculation method can be consulted with the CDM methodologies listed in Table 2.

To compare the GHG emission reduction among different measures and products, the reduction in carbon intensity (ERI) (tCO_{2eq}/USD), as shown in Eq. (5), is proposed

$$ERI = \frac{ER}{price \times C} \tag{5}$$

where

ERI	Reduction in carbon intensity (tCO_{2eq}/USD)
ER	GHG emission reduction (tCO_{2eq}/year)
price	Market price of product (USD/ton of product)
C	Annual production of product (ton of product/year)

The ERI is defined as the proportion between the GHG emission reductions and the value of product produced in the factory in which the measure was adopted. Similar to energy assessment, this index indicates environmental benefit in terms of reduced carbon intensity from implementing the ECM. A high value means that the measure has the environmental benefit higher than those of a low value in the same sector. Moreover, this index can be used to estimate the potential for GHG emission reduction per product value from implementing the measure being considered.

The value calculated from Eq. (5) is the ERI of each ECM. To compare the aggregate ERI for each product and each measure category, the average for the product and measure category of ERI can be calculated, as shown in Eq. (6):

$$ERI_{PM} = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} ER_{i,j,M}}{\sum_{i=1}^{m}(price_P \times C_{i,P})} \tag{6}$$

where

ERI_{PM}	Average reduction in carbon intensity of product P (olefin and aromatic) due to ECMs under category M
$ER_{i,j,M}$	GHG emission reduction in factory i due to ECMs j under category M (tCO_{2eq}/year)
$price_P$	Market price of product P (USD/ton of product P)
$C_{i,P}$	Annual production of product P in factory i (ton of product P/year)
n	Number of ECMs under category M in factory i
m	Number of factories producing product P
i	Index number of factories producing product P
j	Index number of ECMs under category M
P	Petrochemical products
M	Category of ECMs

Assessment of energy consumption reduction cost

To study the real costs incurred in executing the ECMs, the capital expenditure data and operation and maintenance cost of each measure from each plant were collected for analysis, and the assessment results are presented in the form of an index for energy saving on the equivalent annual investment cost of ECM (TJ/USD), as shown in Eq. (7). This index reflects the cost effectiveness in terms of amount of energy that can be reduced for one dollar investments. A high value means that the measure has a better energy cost effectiveness higher than those of a low value.

$$EnROI = \frac{EnR}{EAC} \tag{7}$$

where:

EnROI	Energy consumption reduction on investment cost (TJ/USD)
EnR	Energy consumption reduction (TJ/year)
EAC	Equivalent annual investment cost of an ECM calculated by Eq. (8) (USD/year)

$$EAC = Inv\frac{r(1+r)^{n-1}}{((1+r)^n-1)} + OM \tag{8}$$

where:

EAC	Equivalent annual investment cost allocated over the measure's lifetime of n years with a discount rate of r % (USD/year)
OM	Estimated operating and maintenance cost of the measure (USD/year)
Inv	Investment cost of the measure (USD)
n	lifetime of the measure (years)
r	discount rate (%)

The investment cost (Inv) is the cost of the equipments and/or the system used in the measure including installation and/or implementation cost. They were obtained from the sample factories. The lifetime (n) is technical lifetime of the equipments estimated by the sample factories. The discount rate (r) being used to calculate Eq. (8) is usually a weighted average cost of capital (WACC) of the company that depends on the capital structure, cost of debt, cost of equity, and corporate tax rate of the company in which the measure is implemented. It is a financial factor and does not affect the performance of the ECM being considered. To eliminate the effect of the financial structure of companies and make the EROI comparable among ECMs, in this research, the discount rate was set to be the average minimum loan rate (MLR) of the commercial banks in Thailand, which was approximately 7%.

The value calculated from Eq. (7) is the EnROI of each ECM. To compare the aggregate EROI for each product and each category of measures, the average of the product and measures category of EROI can be calculated, as shown in Eq. (9):

$$EnROI_{PM} = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} EnR_{i,j,M}}{\sum_{i=1}^{m}\sum_{j=1}^{n} EAC_{i,j,M}} \tag{9}$$

where

$EnROI_{PM}$	Average energy consumption reduction on investment cost of product P (olefin and aromatic) due to ECMs under category M (TJ/USD)
$EnR_{i,j,M}$	Energy consumption reduction in factory i due to ECM j under category M (TJ/year)
$EAC_{i,j,M}$	Equivalent annual investment cost of an ECM j under category M in factory i (USD)

Assessment of GHG emission reduction cost

Similar to EnROI, the cost of GHG emission reduction and the assessment results are shown in the form of an index for GHG emission reduction on an equivalent annual investment cost of ECM (tCO_{2eq}/USD), as shown in Eq. (10). This index reflects the cost effectiveness in terms of amount of GHG that can be reduced for one dollar investments. A high value means that the measure has a better environmental cost effectiveness higher than those of a low value.

$$EROI = \frac{ER}{EAC} \quad (10)$$

where:

EROI GHG emission reduction on investment cost (tCO_{2eq}/USD)
ER GHG emission reduction (tCO_{2eq}/year)
EAC Equivalent annual investment cost of an ECM, taking into account the time-value of money, calculated by Eq. (8) (USD/year)

The value calculated from the Eq. (10) is the EROI of each ECM. To compare the aggregate EROI for each product and each category of measures, the average of the product and measures category of EROI can be calculated, as shown in Eq. (11):

$$EROI_{PM} = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} ER_{i,j,M}}{\sum_{i=1}^{m}\sum_{j=1}^{n} EAC_{i,j,M}} \quad (11)$$

where:

EROI$_{PM}$ GHG emission reduction on investment cost of product P (olefin and aromatic) due to ECMs under category M (tCO_{2eq}/USD)
ER$_{i,j}$ GHG emission reduction in factory i due to ECM j under category M (tCO_{2eq}/year)
EAC$_{i,j}$ Equivalent annual investment cost of an ECM j under category M in factory i (USD/year)

Economic feasibility analysis

The economic feasibility of the ECMs can be assessed by the proposed indices. Normally, the concept for assessing the feasibility of energy saving measure is comparing the total cost of implementing the measure (Investment cost including other necessary expenses) with the benefit gained from energy saving. If the benefit is higher than the cost, the measure is considered to be economically feasible. Furthermore, in market with carbon trading mechanism, benefit from carbon credit will also be taken into account.

The GHG abatement cost (USD/tCO_{2eq}) of the ECM can be expressed as the following equation.

$$\text{GHG Abasement cost} = \frac{\text{EAC}-\text{EnR} \times \text{Price}_{\text{En}}}{\text{ER}} \quad (12)$$

where:

EAC Equivalent annual investment cost as described in Eq. (8) (USD/year)
EnR Energy consumption reduction (TJ/year)
ER GHG emission reduction (tCO_{2eq}/year)
Price$_{En}$ Price of energy (USD/TJ)

Since EnR = EnROI × EAC and EROI = ER/EAC, therefore Eq. (12) can be written as

$$\text{GHG Abasement cost} = \frac{1-\text{EnROI} \times \text{Price}_{\text{En}}}{\text{EROI}} \quad (13)$$

The measure being considered will be economically feasible if the GHG abatement cost is lower than the price of carbon credit or when the following criteria meets:

$$\text{Abasement cost} \le \text{Credit}_C$$

where Credit$_C$ is price of carbon credit (USD/tCO_{2eq}). Substituting Eq. (13), the criteria becomes

$$\frac{1-EnROI \times \text{Price}_{En}}{EROI} \le Credit_C$$

or

$$\text{EROI} \times \text{Credit}_C + \text{EnROI} \times \text{Price}_{\text{En}} \ge 1 \quad (14)$$

where:

EROI GHG emission reduction on investment cost of the measure being considered (tCO_{2eq}/USD)
EnROI Energy consumption reduction on investment cost of the measure being considered (TJ/USD)
Credit$_C$ Price of carbon credit (USD/tCO_{2eq})
Price$_{En}$ Price of energy (USD/TJ)

The economic feasibility of ECM can be assessed with the above criteria. The criteria in inequality Eq. (14) divided the region in EROI-EnROI plane into two zones, which are the economically feasible zone and the economically infeasible zone as shown in Fig. 1. In case of having carbon trading mechanism, the measures that have EROI and EnROI in the region above the line ($EROI \times Credit_C + EnROI \times Price_{En} = 1$) will be economically feasible. On the other hand, without carbon credit ($\text{Credit}_C = 0$), the measure on the right hand side of the line ($EnROI = 1/Price_{En}$) will be feasible. Any changes in price of energy and carbon credit will change EnROI and EROI axis intercepts and will affect the region of economically feasible zone.

Assessment of energy saving and GHG emission reduction potential

The potential for energy saving and GHG emission reduction per product value then can be estimated by calculating the summation of the indices EnRI and ERI of all measures that meet economic feasibility criteria, as shown in Eqs. (15) and (16) respectively.

$$EnR_{potential} = \sum_{i}^{feasible} EnRI_i \quad (15)$$

$$ER_{potential} = \sum_{i}^{feasible} ERI_i \quad (16)$$

where:

EnRI$_{potential}$ Potential for energy consumption reduction (TJ/USD)
ERI$_{potential}$ Potential for GHG emission reduction (tCO_{2eq}/USD)
EnRI$_i$ Reduction in energy intensity (TJ/USD)
ERI$_i$ Reduction in carbon intensity (tCO_{2eq}/USD)
i Index number for measures that are economically feasible

Results and discussion

The energy saving and the GHG emission reductions resulting from implemented ECMs implemented in each year during the 2010–2012 period are shown in Table 3. The information regarding each measure is shown in Table 4. From Table 3, the values of EnR and ER in 2010 are much higher than those in 2011 and 2012 because the measure “Natural gas-based cogeneration plant” was implemented in 2010. This measure reduced energy consumption and GHG emission by 5082 TJ/year and 419,759 tCO_{2e}/year, respectively, as shown in Table 4.

There were 18 ECMs adopted in the sample plants. In Table 4, the codes are assigned to each measure for further discussion in this paper. The codes are in the following format: P/CC No.,where

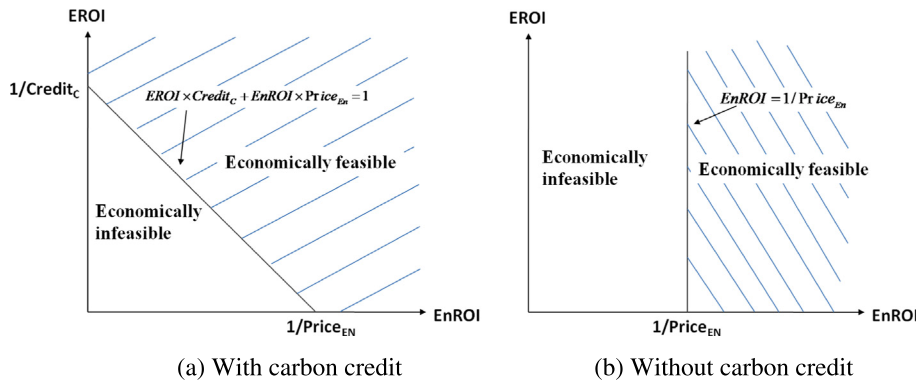


Fig. 1. Economic feasibility criteria for energy conservation measures in EROI-EnROI plane.

P Products, where "O" stands for "Olefin" and "A" stands for "Aromatic".
CC Abbreviation of category of measure as shown in Table 2.
No measure number in category CC.

For example, O/SO1 means the measure number "1" in "steam optimization" category implemented in a "Olefin" plant.

From Table 4, most of these measures are found to concur with the findings on the ECMs of the petrochemical industries of Taiwan (Lu et al., 2013) and Iran (Mohammadi et al., 2013) and those reported by Neelis et al. (2008). The total GHG emission reduction and total energy saving during the 2010–2012 period are 484,580 tCO_{2eq}/yr and 5712 TJ/yr, or 5.4% and 3.7% of the total GHG emissions (8,845,000 tCO_{2eq}/year) and total energy consumption (153,272 TJ/year) in 2009 (Kanchanapiya et al., 2014), respectively.

Olefin group

Energy consumption and GHG emission reduction

For olefin products, the olefin plants carried out 11 ECMs, as shown in Table 4. The total amount of GHG emissions for the sample plants is 471,276 (tCO_{2eq}/yr). The measure category most capable of reducing GHG emissions is CO, followed by WE and EE, with 89%, 7% and 3% of the total GHG emission reduction in the olefin group, respectively. The energy saving from every measure executed by the sample plants is 5476 TJ/yr. The measure category found most effective in reducing the energy consumption is CO, followed by WE and EE. The ranking order is similar to the order of the measure ranking in GHG emission reduction, 89%, 5.4% and 4.6% of the total energy reduction in the olefin group, respectively. The types of measures adopted and implemented in olefin group are similar to those of the upstream petrochemical industry in Taiwan. The most effective measures for reducing the energy consumption are the process heat saving potential (equivalent to EE,45.4%), followed by recycling and energy recovery (equivalent to WE, 22.4%) and combined heat and power (equivalent to CO) (Lu et al., 2013).

Under the CO category, there is one ECM, "O/CO1: Natural gas-based cogeneration plant". The amount of GHG emission reduction for this measure is 419,759 tCO_{2eq}/yr, or 89% of the total GHG emission reduction for the olefin group. For energy conservation, this measure reduced energy by 4895 TJ/yr, or 89% of the total energy conserved in the olefin group. The GHG emission reduction proportion is higher than the proportion of energy conserved because the GHG emission factor of the co-generation system reduces from 81.95 tCO_2eq/TJ to 56.10 tCO_{2eq}/TJ due to switching the fuel to a low carbon-intensive one. Although the CO category is highly effective for GHG emission reduction, the number of plants adopting the measure is rather low due to the high investment cost and the requirement for plants to have a separate sub-system to generate electrical power and thermal energy in steam.

The WE category includes three measures. The measure named "O/WE1: Waste heat recovery at boiler feed water" is a measure for recovering waste heat by installing an effluent heat exchanger for the boiler feed water (BFW) supplied to the cracking furnace and is capable of reducing the GHG emission by 18,697 tCO_{2eq}/yr, or 4% of the total GHG emission reduction in the olefin group. The remaining two measures, "O/WE2:Waste heat recovery at acetylene reactor feed" and "O/WE3:Flare loss management," reduce the GHG emission by 9709 and 6907 tCO_{2eq}/yr, respectively. According to a study by Mohammadi et al. (2013), Iran's petrochemical industry also adopted waste heat recovery measures. The measures for the installation of waste heat recovery boilers at Imam, heat recovery steam generator and flue gas at Fajr and recovery of flare gases at Tabriz petrochemical factories reduced GHG emissions by 80,000, 60,000, and 8000 tCO_{2eq}/yr, respectively. The waste energy recovery was able to reduce the energy consumption by 123 TJ/yr, or 11% of total energy saving in the olefin group.

Table 4 shows that the EE category of ECMs to be the highest in number due to these measures covering small measures requiring minimal investment costs instead of consisting of large measures requiring high investment costs for the installation or replacement of equipment. There are five measures under EE. The measure "O/EE1: Advanced process control" is the most effective in GHG emission reduction, reducing GHG emissions by 11,310 tCO_{2eq}/yr, or 2% of the total GHG emission reduction for the olefin group. In this measure, a model for the production control systems was created to achieve an automatic function to help reduce energy consumption as well as the number of operators. For energy saving, this measure saves 202 TJ/yr, or 17% of the total energy reduction in the olefin group.

Reduction in energy intensity and carbon intensity

The calculation results of the EnRI and ERI for each measure and each category of measures are summarized in Table 4 and Table 5, respectively. The category with the highest ERI_{PM} is CO, followed by WE, EE, and SS. The order was similar to the case of the GHG emission reduction (ER) previously described. Furthermore, the $ERI_{PM}$of CO is 402 tCO_{2eq}/million USD of product, which is higher than the ERI_{PM} of other methodologies by 35–80 times. However, the measure requires further consideration of the investment required to execute the measure to assess the suitability of the adoption of the measure. For the

Table 3
Energy saving and GHG emission reduction during the 2010–2012 period.

Year	Energy consumption reduction (EnR) (TJ/yr)	GHG emission reduction(ER) (tCO_{2eq}/yr)
2010	5045	428,224
2011	374	33,645
2012	293	22,711
Accumulate	5712	484,580

Table 4
Summary of energy conservation measures.

Types of measures	Name of energy conservation measures	Code	EnR (TJ/yr)	ER (tCO_{2eq}/yr)	EnRI (TJ/10^6\$ of Product)	ERI (tCO_{2eq}/10^6\$ of Product)	EnROI (GJ/\$)	EROI (tCO_{2eq}/\$)	measure lifetime (yr)	EAC (USD/yr)	Abatement cost (USD/tCO_2)
Steam saving and steam loss reduction	Steam trap replacement	O/SS1	19	1060	0.011	0.592	4.45	0.25	5	4273	−118.75
	Condensate return improvement	O/SS2	15	814	0.017	0.938	∞	∞	N/A	0	−126.23
Steam optimization	Platforming unit steam optimization	A/SO1	136	7603	0.120	6.731	0.24	0.01	20	556,844	−49.29
	High performance tray replacement at platforming splitter	A/SO2	15	862	0.014	0.763	0.94	0.05	15	16,023	−100.61
Cogeneration	Natural gas-based cogeneration plant	O/CO1	5082	419,759	4.869	402.167	0.34	0.03	30	14,969,179	−44.22
Energy efficiency	Advanced process control	O/EE1	202	11,310	0.113	6.313	4.89	0.27	20	41,344	−118.69
	Furnace energy efficiency	O/EE2	39	2183	0.022	1.219	∞	∞	N/A	0	−122.38
	Cooling fan replacement	O/EE3	4	475	0.005	0.547	0.13	0.02	8	30,137	5.76
	Boiler energy efficiency	O/EE4	5	284	0.006	0.327	0.09	0.005	5	58,454	85.23
	Demineralized water pump optimization	O/EE5	0.7	78	0.001	0.090	0.10	0.01	20	7045	28.85
	Clean convection zone of fire heater	A/EE1	56	3137	0.049	2.777	2.76	0.15	1	20,292	−115.81
	Mercury removal unit heat optimization	A/EE2	22	1212	0.001	0.118	∞	∞	N/A	0	−124.34
	Platforming feed optimization by bypass fin-fan	A/EE3	5	280	0.004	0.248	3.90	0.22	15	1283	−117.74
	Mercury removal unit electrical optimization	A/EE4	0.9	133	0.019	1.073	∞	∞	N/A	0	−46.35
	Instrument air optimization	A/EE5	0.5	77	0.000	0.068	∞	∞	N/A	0	−44.48
Waste energy recovery	Waste heat recovery at boiler feed water	O/WE1	107	18,697	0.102	17.913	0.29	0.05	15	370,397	−19.39
	Waste heat recovery at acetylene reactor feed	O/WE2	67	9709	0.037	5.420	0.33	0.05	15	203,921	−26.27
	Flare loss management	O/WE3	123	6907	0.069	3.856	∞	∞	N/A	0	−121.98
Total			5712	484,580							

$EnRI_{PM}$ index, Table 5 shows that the category with the highest $EnRI_{PM}$ is CO, followed by WE, EE, and SS, similar to the order of the ERI_{PM}. The CO category that reduces fuel consumption by installing a cogeneration system is the methodology with the highest reduction of both GHG emission and energy consumption compared to the other categories of ECMs.

Aromatic group

Energy consumption and GHG emission reduction

In the aromatic product group, Table 4 shows seven ECMs being adopted by aromatic plants covering two categories. The amounts of GHG emission reduction and energy saving from every measure of the sample plants are 13,304 tCO_{2eq}/yr and 235 TJ/yr, respectively. The category that reduces the GHG emissions and energy consumption the most is SO, by 63.6% and 64.1% of the total GHG emission reduction and energy saving in the aromatic group, respectively.

The steam-related ECMs have been widely adopted by the upstream petrochemical industry because steam is a key energy source for the production process. Table 4 shows that the steam-related ECMs of aromatic plants are all under the SO category, while those of the olefin plants are under the SS category. The SO category includes two ECMs, and the measure "A/SO1: Platforming unit steam optimization" is the measure with the highest GHG emission reduction at 7603 tCO_{2eq}/yr, or 57% of the total GHG emission reduction in the aromatic group. This measure requires the design and installation of new heat exchangers with the energy consumption efficiency improved by 3.57%, thereby resulting in a reduction of the energy consumption by 136 TJ/yr, or 58% of the total energy saving in the aromatic group. However, this measure requires high investment costs, as shown in Table 4. The other measure is "A/SO2: High performance tray replacement at platforming splitter," which can reduce the GHG emission by 862 tCO_{2eq}/yr. In the aromatic production process, platformate splitter separates light aromatic from heavy aromatic. This measure changes the tray in the platformate splitter process to a higher performance one that can separate more efficiently and consequently consume less steam.

The EE category is also the most frequently adopted by the aromatic groups. The measure A/EE1 has the highest ER at 3137 tCO_{2eq}/yr, or 24% of the total ER in the aromatic group. This measure involves the improved efficiency of the fired heaters by cleaning the convection zone for better heat transfer performance. This measure reduces the energy consumption by 56 TJ/yr, or 24% of the total energy saving in the aromatic group. Compared to the olefin plants, the aromatic plants appear to have lower aggregate EnR and ERn than those of the olefin plants. However, the total investment cost required under

Table 5
Summary of average indices.

Types of measures	Product group	EnR (TJ/yr)	ER (tCO_{2eq}/yr)	EnRI (TJ/10^6\$ of Product)	ERI (tCO_{2eq}/10^6\$ of Product)	EnROI (GJ/\$)	EROI (tCO_{2eq}/\$)
Steam saving and steam loss reduction	Olefin	34	1874	0.01	0.70	7.96	0.44
Steam optimization	Aromatic	151	8465	0.13	7.49	0.26	0.01
Cogeneration	Olefin	4895	419,759	4.69	402.17	0.33	0.03
Energy efficiency	Olefin	251	14,330	0.09	5.39	1.83	0.10
	Aromatic	84	4839	0.07	4.28	3.91	0.22
Waste energy recovery	Olefin	297	35,313	0.10	12.46	0.52	0.06

this category of aromatic plants is much lower than that of the olefin plants. The discussion regarding the cost effectiveness of measures will be presented in Economic analysis of energy conservation measures section.

Reduction in energy intensity and carbon intensity

The results of ERI_{PM} and $EnRI_{PM}$ of the aromatic group are shown in Table 5. The category with the highest ERI is SO, followed by EE, with values of 7.49 and 4.28 tCO_{2eq}/million USD of product, respectively. The $EnRI_{PM}$ of the SO and EE categories are 0.13 and 0.07 TJ/million USD of product, respectively. Compared to the ERI_{PM} of the olefin group, the ECMs regarding the steam system implemented in the aromatic plants are higher than those of the olefin plants by approximately 10 times, indicating that the aromatic group achieved higher steam use reduction to product value ratio than the olefin group. However, the context in which the measures are implemented is quite different. While the measures in the olefin plants relate reducing steam loss at some specific points in the production process, the measures in the aromatic plants improve the process efficiency, which helps reducing the overall specific energy consumption. However, the measures in the aromatic plants also require higher capital expenditure than those of the olefin plants. Conversely, the ERI_{PM} of the EE category in the aromatic plants is lower than that of the olefin plants by approximately 0.8 times. When considering each measure under EE, there are four measures, O/EE2, O/EE4, A/EE1 and A/EE3, regarding the thermal efficiency improvement. The measure O/EE2 is the measure that improves the thermal efficiency of the cracking furnace by several activities, such as reducing excess oxygen, recovering the furnace's insulation condition and controlling the draft pressure. The olefin cracking furnace is the highest thermal energy consuming equipment in the olefin production process. Improving its efficiency can greatly contribute to reducing the energy consumption of the whole process. The measure O/EE4 replaces the boiler duct insulator to reduce heat loss. The measure A/EE1 improves the heat transfer performance of fired heaters by cleaning the convection zone. The A/EE3 increases the thermal efficiency of air-cooled heat exchangers. The overall performance of air-cooled heat exchangers depends primarily on the effectiveness of two basic elements: the fin tube and the air moving equipment. This measure reduces fouling in the heat exchangers by installing a bypass fin-fan to increase the temperature of the platforming feed, resulting in reduced fuel gas used at the platformer heater. Although these measures were applied to different equipment, they all regard heat transfer performance improvement. Among these four measures, the measure with the highest EnRI and ERI is the measure A/EE1(0.07 TJ/million USD, 4.28 tCO_{2eq}/million USD), followed by O/EE2(0.02 TJ/million USD, 1.22 tCO_{2eq}/million USD),O/EE4(0.01 TJ/million USD, 0.33 tCO_{2eq}/million USD), and A/EE3 (0.004 TJ/million USD, 0.25 tCO_{2eq}/million USD). These measures had different investment costs, and their economic cost effectiveness needs to be taken into account and considered as well.

Economic analysis of energy conservation measures

Energy and environmental benefit on investment cost

The equivalent annual investment costs of the ECMs surveyed are shown in Table 4. There are six measures without investment required, which are O/SS2, O/EE2, A/EE2, A/EE4, A/EE5, and O/WE3. Among these measures, the measure most capable of reducing energy consumption and GHG emission is O/WE3, followed by O/EE2, A/EE2, O/SS2, A/EE4 and A/EE5. For O/WE3, in the demethanizer and hydrogen separation unit of the olefin production process, the tail gas is a residue gas composed of hydrogen and methane that will be generated as a by-product. Normally, this tail gas would be treated by a flaring process. The O/WE3 measure recovers this tail gas, uses it as process fuel. This measure could reduce energy consumption and GHG emissions by 123 TJ/yr and 6907 tCO_{2eq}/yr, respectively. The O/EE2 measure improves the thermal efficiency of the cracking furnace and could reduce the energy consumption and GHG emissions by 39 TJ/yr and 2183 tCO_{2eq}/yr, respectively. In the aromatic production process, there is a mercury removal unit to remove the mercury from the condensate to enhance the efficiency and lifetime of the catalyst used in the continuous catalyst regeneration platformer. The A/EE2 and A/EE4 increase the inlet temperature of the mercury removal unit by adjusting the number of operating fin-fans in the air cooler with no effect on the performance of the mercury removal or the quality of the products. The higher inlet temperature will reduce the fuel and electrical power use. These two measures can reduce energy consumption and GHG emissions by 23 TJ/yr and 1345 tCO_{2eq}/yr, respectively. The O/SS2 measure controls the continuous valves to operate more efficiently so that the amount of return condensate and feed-in water to the boiler will be optimized, consequently reducing the energy consumption. This measure can reduce the energy consumption and GHG emissions by 15 TJ/yr and 814 tCO_{2eq}/yr, respectively. This type of measure is applicable for both olefin and aromatic production processes and other industries that use steam in the production process. The A/EE5 measure reduces the air pressure used in the process to reduce the electrical power use in the air compressor. This measure can reduce the energy consumption and GHG emissions by 0.5 TJ/yr and 77 tCO_{2eq}/yr, respectively. This type of measure is also applicable for both olefin and aromatic plants and other industries using air pressure in the production process. Such measures that require no investment cost should be promoted by upstream petrochemical plants with top priority from an economic perspective. However, these measures are usually small and the GHG emission reduction capability is not large compared to measures requiring investments.

The EnROI and EROI of each ECM requiring capital expenditure are shown in Table 4. Almost all of the measures have EnROI and EROI within the range of less than 1 GJ/USD and 0.1 tCO_{2eq}/USD, respectively, except for four measures: O/EE1,O/SS1,A/EE3 and A/EE1. When the olefin group is considered, the most cost effective measure with noticeably high EnROI and EROI values is O/EE1, followed by O/SS1, with EnROI at 4.89 and 4.45 GJ/USD and EROI at 0.27 and 0.25 tCO_{2eq}/USD, respectively. The O/EE1 controls the variables in a process by installing a distributed control system (DCS) and advanced process control program to control the stability of the process and to improve the thermodynamic efficiency of the plant by optimizing the pressure profile of the process to reduce the energy consumption. Although this measure requires the highest capital expenditure, it is the most cost effective measure for reducing GHG emissions and energy consumption. Moreover, this measure also has a relatively high ERI and EnRI. The O/SS1 reduces the steam loss from steam traps by replacing failed steam traps in the steam distribution system of the plant. This measure is a relatively cost effective measure in reducing GHG emissions and energy consumption but has a low ERI and EnRI. The CO1 is capable of reducing the most GHG emissions compared to the product value (see Olefin group section) is not the most cost effective measure when considering the GHG emission reduction per investment cost.

For the average EnROI and EROI for each category of measures and products, as shown in Table 5, the category under which the measures have the highest $EROI_{PM}$ is SS, followed by EE, WE and CO with values of 0.44, 0.1, 0.06 and 0.03 tCO_{2eq}/USD, respectively. The ranking of $EROI_{PM}$ is different from that of the ERI_{PM} (see Olefin group section), especially for the SS and CO categories. The SS category has the highest EnROI and EROI but the lowest EnRI and ERI. The CO category tends to be the opposite of SS. In other words, the CO category involves an extremely high investment with high GHG emission reduction and energy saving. However, the amount of GHG emission reduction per investment cost is found to be rather low compared to other categories.

When the aromatic group is considered, the most cost effective measure with noticeably high EnROI and EROI values is A/EE3, followed by A/EE1, which are both under the EE category, with an EnROI at 3.90 and 2.76 GJ/USD and EROI at 0.22 and 0.15 tCO_{2eq}/USD, respectively. The A/EE3 increases the thermal efficiency of air-cooled heat exchangers as previously described. This measure is a relatively cost effective measure for reducing GHG emissions and energy consumption but has a relatively low ERI and EnRI, as shown in Table 4. The A/EE1 enhances the heat transfer performance of heat exchangers by cleaning the convention coil of a fired heater. Such measures are usually able to be applied to the olefin group as well. This measure is a relatively cost effective measure in reducing GHG emissions and energy consumption and has a moderate ERI and EnRI, as shown in Table 4. When the capability of reducing GHG emissions is considered based on ER (see data in Table 4), the A/SO1 measure appears capable of reducing the most GHG emissions. However, this measure's EROI is only 0.01 tCO_{2eq}/USD. This finding indicates that measures that are able to significantly reduce GHG emissions might be unsuitable measures from an economic perspective.

Considering the mean EnROI and EROI for each measure category and product, as shown in Table 5, the category with the highest average EROI is EE, followed by SO; the $EnROI_{PM}$ are 3.91 and 0.24 GJ/USD and the $EROI_{PM}$ are 0.22 and 0.01 tCO_{2eq}/USD, respectively. Comparing the $EROI_{PM}$ and $EnROI_{PM}$ of the EE category to those of olefin products, the results show that the measures implemented in the aromatic plants are more cost effective than those of the olefin plants. When the order of GHG emission reduction is compared based on ERI_{PM}(see Aromatic group section), the order appears to be opposite. This result is because the measures under the SO category have relatively high investment compared to the EE category, especially measure A/SO1, which required an advanced level of technology, leading to the import of a system and equipment with high costs. When considering each measure in Table 4, the four measures regarding thermal efficiency improvement, O/EE2, O/EE4, A/EE1 and A/EE3, previously discussed in terms of ERI and EnRI in Reduction in energy intensity and carbon intensity section, show a different order in the economic perspective. The most cost effective measure is O/EE2 (no investment cost), followed by A/EE3, A/EE1 and O/EE4.

Economic feasibility

Fig. 2 provides the EnROI-EROI plane for ECMs adopted in the sample plants. The economically feasible measures are those which are on the right zone. The price of energy used in this research is the average natural gas price of year 2010, i.e. 6.85 USD/GJ. Therefore, the EnROI axis-intercept equals 1/6.85 = 0.146 GJ/USD. From Fig. 2, without carbon trading mechanism, almost all measures except O/EE3, O/EE4, and O/EE5 are on the right side and are economically feasible. However, the non-cost effective measures on the left side can be promoted by carbon trading mechanism. In Thailand, a domestic institutional framework for GHG mitigation called the Thailand Voluntary Emission Reduction Program (T-VER) is currently being developed. The mechanism of the program is similar to the CDM. An emission reduction project can earn saleable Thailand verified emission reductions (TVERs) credits that will be tradable in a domestic carbon market, currently being developed as well. Therefore, at present, the price of carbon credit is not available. However, there is a study conducted regarding carbon pricing in domestic market and the suitable price of carbon credit is suggested to be approximately 20 USD/tCO_{2eq} (TGO, 2015). Therefore, in this research we assumed the carbon credit to be this price in case that the plants can get additional benefit from selling carbon credit. With carbon credits at 20 USD/tCO_{2eq}, EROI axis-intercept of the criteria line will change to $1/Credit_C = 0.05$ tCO_{2eq}/USD and the measure O/EE3 will become economically feasible (above the line), as shown in Fig. 2.

Any change in prices of energy and carbon credit will change EnROI and EROI axis intercepts and then affects the feasible-infeasible zones as shown in Fig. 3. For instance, in cases of without carbon trading mechanism, if the price of energy decreases to 4 USD/GJ ($1/Price_{EN} =$ 0.25 GJ/USD), EnROI axis-intercept will move rightwards as presented in Fig. 3 and the measure A/SO1 will fall into infeasible zone, which means that the benefit of energy saving will not cover implementation cost of the measure. Similarly, if the price of energy decreases to 3.4 USD/GJ ($1/Price_{EN} = 0.29$ GJ/USD) and 3 USD/GJ ($1/Price_{EN} =$ 0.33 GJ/USD), the measure O/WE1 and the measures O/WE1, O/CO1 and O/WE2 will become economically infeasible in each case respectively as shown in Fig. 3. Similarly, in case of having carbon trading mechanism, if the price of carbon credit decreases to 5 USD/tCO_{2eq} ($1/Credit_C = 0.2$ tCO_{2eq}/USD), EROI axis-intercept will move upwards as presented in Fig. 3 and then the measure O/EE3 will fall into infeasible zone. On the other hand, if the price of carbon credit increases to 30 USD/tCO_{2eq} ($1/Credit_C = 0.03$ tCO_{2eq}/USD), the measure O/EE5 will become economically feasible.

Change in price of energy or carbon credit will affect the feasible zone on EnROI-EROI plane, but does not affect the values of EnROI and EROI. The EnROI and EROI depend on only their energy and environmental performance in terms of amount of reduced energy and GHG emission, and the equivalent annual investment cost (EAC). Therefore, the EnROI-EROI plane can support decision makers to analyze and evaluate the economic feasibility of the measures under various policies and pricing scenarios of energy and carbon credit. Furthermore, it can be applied in other industries as well.

Potential for energy saving and GHG emission reduction

The energy saving and GHG emission reduction potential can be evaluated by calculating the summation of the EnRI and ERI of all economically feasible measures, respectively. The results are shown in Table 6.

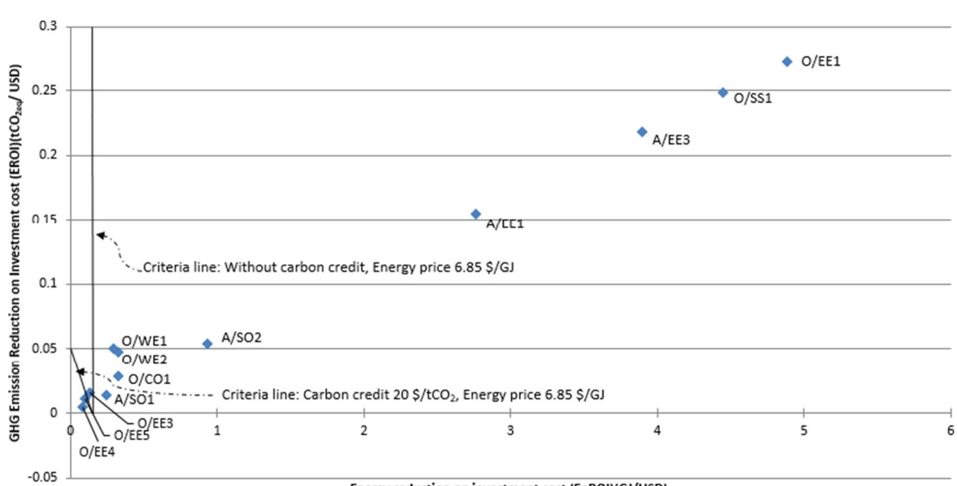


Fig. 2. Economic feasibility of the measures.

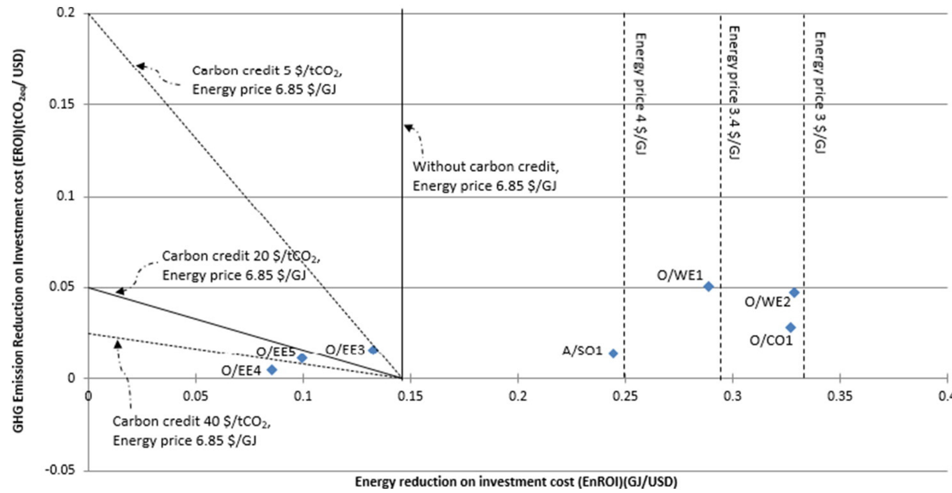


Fig. 3. Effect of change in prices of energy and carbon credit on cost-effectiveness of the measures.

From Table 6, without carbon credit, the potential energy consumption and GHG emission reduction (all measures excluding O/EE3, O/EE4, and O/EE5) were found to be 5.267 TJ/million USD of product and 450.195 tCO_{2eq}/million USD of product, respectively. With carbon credit at 20 USD/tCO_{2eq}, the potential for energy conservation and emission reduction (all measures except O/EE4, and O/EE5) became 5.272 TJ/million USD of product and 450.742 tCO_{2eq}/million USD of product, respectively. The difference between two cases is small since the EnRI and ERI of the measure O/EE3 is small.

Based on the information of GHG abatement cost calculated by Eq. (12) (see Table 4) and reduction in energy and carbon intensity (EnRI and ERI), GHG marginal abatement cost curves were constructed to compare with the results from this research method. Marginal abatement cost curves of GHG reduction (McKinsey&Company, 2009) as well as energy conservation cost supply curves (Worrell et al., 2001) are well-known and common tools used to evaluate the potential for energy efficiency improvement and GHG emission reduction. Fig. 4 provides the marginal abatement cost curves. The horizontal axis in Fig. 4(a) and (b) depicts, respectively, the cumulative energy saving (summation of EnRI) expressed as TJ/USD of product and cumulative emission reduction (summation of ERI) expressed as tCO_{2eq}/USD of product. The vertical axis depicts the GHG abatement cost expressed as USD/tCO_{2eq}, including energy saving benefit from energy efficiency improvement. Without carbon credit trading, the measures with negative abatement cost (energy saving benefit covers investment cost for emission reduction) will be economically feasible. On the other hand, with carbon credit trading, the measures under the dash line (20 USD/tCO_{2eq}) will be economically feasible. From Fig. 4(a), the potential energy saving in case of with and without carbon credit are found to be 5.267 and 5.272 TJ/million USD of product, respectively. From Fig. 4(b), the potential GHG emission reduction in case of with and without carbon credit are found to be 450.195 and 450.742 tCO_{2eq}/million USD of product, respectively. The results from the GHG marginal abatement cost curves are consistent with those of Table 6.

Table 6
Energy consumption and GHG emission reductions potential.

Carbon credit (USD/tCO_{2eq})	Energy saving potential $\left(\sum_{i}^{feasible} EnRI_i\right)$ (TJ/million USD of product)	GHG emission reduction potential $\left(\sum_{i}^{feasible} ERI_i\right)$ (tCO_{2eq}/million USD of product)
0	5.267	450.195
20	5.272	450.742

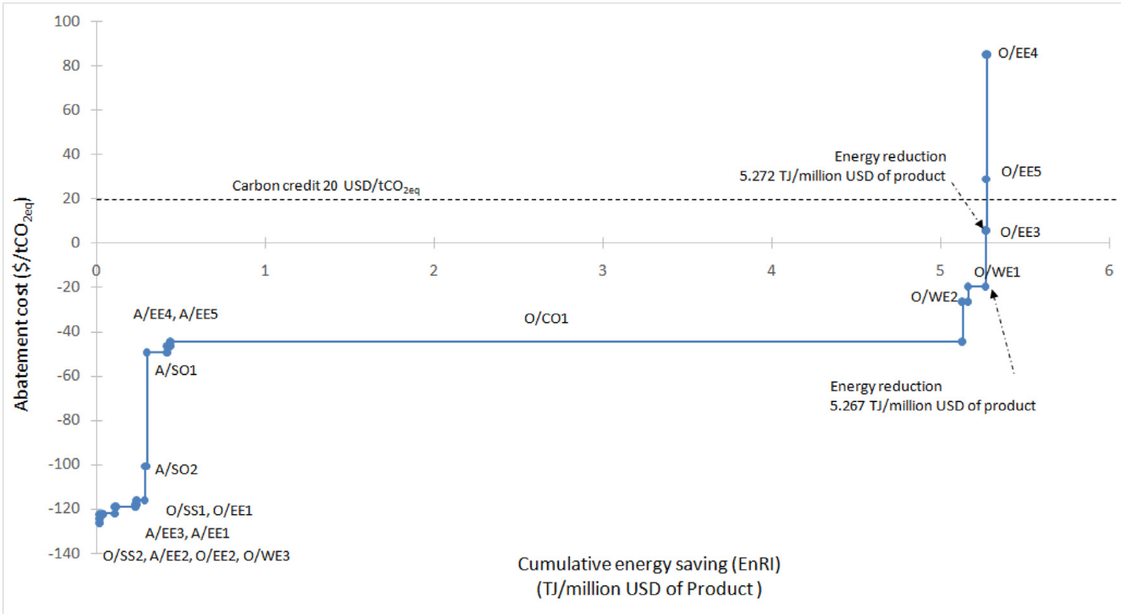
While the GHG marginal abatement cost curve has the advantage of graphically presenting the reduction potential on the horizontal axis, the proposed EnROI-EROI plane has the advantage of graphically presenting the economically feasible resilience of each ECM to various energy and carbon market condition (energy and carbon credit prices). Using the proposed indices has the interpretative benefit that while each index can be used to assess ECM in energy (EnRI) environmental (ERI) and economic (EnROI, EROI) perspectives, applying all indices together can assess the economic feasibility of the ECM and estimate the potentials of energy saving and emission reduction.

The energy and carbon intensities used in this research are normalized by product value in order to compare the performance of different measures between two products (olefin and aromatic). However, in case of comparing the performance of measures within one product, the unit TJ/ton of product and tCO_{2eq}/ton of product are more suitable and should be used instead.

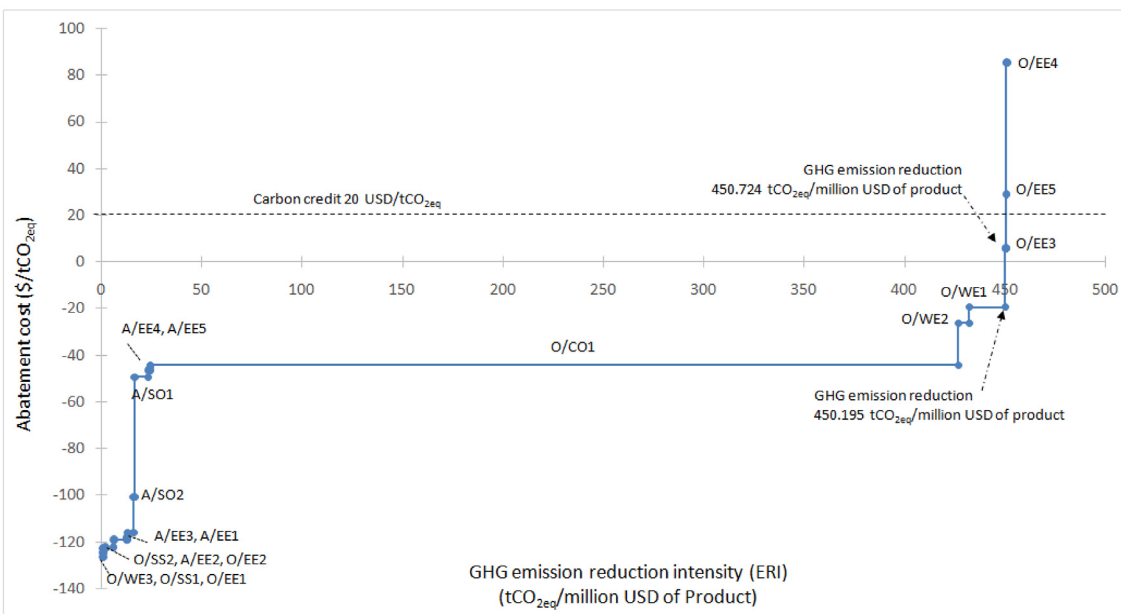
Conclusions

In this research, the performance of energy conservation measures implemented in Thailand's upstream petrochemical industry during the 2010–2012 period were assessed in the energy, environmental and economic perspectives. The data from the energy conservation measures were collected from olefin and aromatic sample plants, accounting for 64% and 55% of Thailand's national capacity, respectively. The measures can be grouped and categorized into the five following categories: 1) steam saving and steam loss reduction (SS), 2) steam optimization (SO), 3) cogeneration (CO), 4) energy efficiency (EE), and 5) waste energy recovery (WE). The GHG emission reduction and energy saving were calculated for each measure using the CDM. This research applied indices to assess the performance of the measures in terms of environmental (ERI), energy (EnRI), and economic cost effectiveness (EnROI and EROI) perspectives and proposed the method to assess the economic feasibility and estimate the energy saving and emission reduction potential by using the four indices.

According to the assessment results from the energy and environmental perspectives, for olefin plants, the category with the highest ERI and EnRI is CO, followed by WE, EE,and SO. The measure most capable of reducing GHG emissions and energy consumption was O/CO1: Natural gas-based cogeneration plant, which reduced 402 tCO_{2eq}/million USD of product and 4.69 TJ/million USD of product, respectively. For the aromatic plants, the category with the highest ERI and EnRI is SO, followed by EE. The A/SO1: Steam trap replacement measure had the highest ERI and EnRI at 6.73 tCO_{2eq}/million USD of product and 0.12 TJ/million USD of



(a) Energy saving potential



(b) GHG emission reduction potential

Fig. 4. GHG marginal abatement cost curves.

product, respectively. Comparing the results of the category with similar measures, EE, the olefin plants have higher ERI and EnRI than the aromatic plants.

From the economic perspective, six measures needed no capital expenditure: O/SS2: Condensate return improvement, O/EE2: Furnace energy efficiency, A/EE2: Mercury removal unit heat optimization, A/EE4: Mercury removal unit electrical optimization, A/EE5: Instrument air optimization, and O/WE3: Flare loss management. Such measures should be promoted by upstream petrochemical plants with top priority from an economic perspective. However, these measures are usually small, and the GHG emission reduction capability is not great compared to the measures requiring investment. Considering the EROI, for olefin plants, the category with the highest $EROI_{PM}$ is SS, followed by EE, WE and CO with values of 0.44, 0.1, 0.06 and 0.03 tCO_{2eq}/USD, respectively, and the measure with the highest EnROI and EROI is O/EE1: Advanced process control. The CO category with the highest ERI and EnRI was found to have the lowest cost effectiveness. For aromatic plants, the category under which the measures have the highest $EROI_{PM}$ is EE, followed by SO, with values of 0.22 and 0.01 tCO_{2eq}/USD, respectively, and the measure with the highest EnROI and EROI is A/EE3: Platforming feed optimization by bypass fin-fan.

By applying EnROI-EROI plane, the result shows that, without carbon credit benefit, almost all measures except O/EE3: Cooling fan replacement, O/EE4: Boiler energy efficiency, and O/EE5: Demineralized water pump optimization are economically feasible and the energy saving potential and GHG emission reduction potential are 5.267 TJ/million

USD of product and 450.195 tCO_{2eq}/million USD of product, respectively. With carbon credit at 20 USD/tCO_{2eq}, measure O/EE3: Cooling fan replacement will become economically feasible and the potentials for energy saving potential and GHG emission reduction potential become 5.272 TJ/million USD of product and 450.742 tCO_{2eq}/million USD of product, respectively.

This research has presented important information regarding energy conservation measures implemented in Thai upstream petrochemical industry with an in-depth analysis. The evaluation and assessment method proposed in this research can support decision makers to analyze and evaluate the economic feasibility of the measures under various policies and pricing scenarios of energy and carbon credit and can be applied in other industries as well. The results of this research can be used as a benchmark and will be beneficial to upstream petrochemical plants and other industries for sustainable industrial development.

Nomenclature

ECM	Energy conservation measure
EnRI	Reduction in energy intensity
ERI	Reduction in carbon intensity
EnROI	Energy consumption reduction on investment
EnROI	Emission reduction on investment
EAC	Equivalent annual investment cost
SS	Steam saving and steam loss reduction
SO	Steam optimization
CO	Cogeneration
EE	Energy efficiency
WE	Waste energy recovery
O/SS1	Steam trap replacement
O/SS2	Condensate return improvement
A/SO1	Platforming unit steam optimization
A/SO2	High performance tray replacement at platforming splitter
O/CO1	Natural gas-based cogeneration plant
O/EE1	Advanced process control
O/EE2	Furnace energy efficiency
O/EE3	Cooling fan replacement
O/EE4	Boiler energy efficiency
O/EE5	Demineralized water pump optimization
A/EE1	Clean convection zone of fire heater
A/EE2	Mercury removal unit heat optimization
A/EE3	Platforming feed optimization by bypass fin-fan
A/EE4	Mercury removal unit electrical optimization
A/EE5	Instrument air optimization
O/WE1	Waste heat recovery at boiler feed water
O/WE2	Waste heat recovery at acetylene reactor feed
O/WE3	Flare loss management

Acknowledgement

The authors sincerely thank the National Research University Project, Office of Higher Education Commission (WCU-58-015-EN) for financial supports of this research project, Thai petrochemical companies for providing relevant data and information for research analysis.

References

Charmondusit K, Keartpakpraek K. Eco-efficiency evaluation of the petroleum and petrochemical group in the map Ta Phut Industrial Estate, Thailand. J Clean Prod 2011;19:241–52.

Department of Alternative Energy Development and Efficiency (DEDE). Energy Ministry of Thailand. Energy in Thailand. facts and figures; 2013y.

Department of Alternative Energy Development and Efficiency (DEDE), Energy Ministry of Thailand. The study of energy consumption criterion in petrochemical industry project; 2007y.

Intergovernmental panel on climate change: IPCC. 2006 IPCC Guidelines for National Greenhouse Gas Inventories; 2016 [Retrieved Dec 10, 2015 from www.ipccnggip.iges.or.jp/public/2006gl/].

Kanchanapiya P, Limphitakphong N, Pharino C, Chavalparit O. Evaluation of greenhouse gas emissions and reduction from the petrochemical industry in Thailand. Greenh Gas Meas Manag 2014;4(2–4):161–77.

Lee S-Y. Existing and anticipated technology strategies for reducing greenhouse gas emission in Korea's petrochemical and steel industries. J Clean Prod 2013;40:83–92.

Lu S-M, Lu C, Tseng K-T, Chen F, Chen C-L. Energy-saving potential of the industrial sector of Taiwan. Renew Sustain Energy Rev 2013;21(0):674–83.

McKinsey&Company. Pathway to a low-carbon economy version 2 of the global greenhouse gas abatement cost curve; 2009.

Mohammadi A, Soltanieh M, Abbaspour M, Atabi F. What is energy efficiency and emission reduction potential in the Iranian petrochemical industry? Int J Greenhouse Gas Control 2013;l12(0):460–71.

Neelis M, Patel M, Blok K, Haije W, Bach P. Approximation of theoretical energy-saving potentials for the petrochemical industry using energy balances for 68 key processes. Energy 2007;32:1104–23.

Neelis M, Worrell E, Masanet E. Energy efficiency improvement and cost saving opportunities for the petrochemical industry. Berkeley: Ernest Orlando Lawrence Berkeley National Laboratory, University of California; 2008 [Retrieved March 1, 2014 from www.energystar.gov/ia/business/industry/Petrochemicals.pdf].

Petroleum Institute of Thailand (PITI). PTIT focus. 2011. Retrieved March 1, 2014 from www.ptit.org/ptit_medias/arlcat_24eb34011729602949d3918abcb71505.pdf.

Thailand Greenhouse gas Management Organization (TGO). Feasibility study of development of international carbon market and carbon pricing for greenhouse gas reduction program; 2015 [Retrieved Jan 10, 2016 from carbonmarket.tgo.or.th/admin/uploadfiles/document/ts_5cfb10f698.pdf].

Tian J, Shi H, Li X, Chen L. Measures and potentials of energy-saving in a Chinese fine chemical industrial park. Energy 2012;46:459–70.

United Nations Framework Convention on Climate Change (UNFCCC). AM0017: steam system efficiency improvements by replacing steam traps and returning condensate version 02; 2005C [Retrieved Jan 10, 2016 from cdm.unfccc.int/methodologies/DB/E8B6YV4LXC0UFS254Q070PF37XPTNG].

United Nations Framework Convention on Climate Change (UNFCCC). AM0048: "New cogeneration project activities supplying electricity and heat to multiple costumers version 3.1.0; 2010C [Retrieved Jan 10, 2016 from cdm.unfccc.int/methodologies/DB/D9S0ST4506RVU6JMZKBV9IDK8WFMUP].

United Nations Framework Convention on Climate Change (UNFCCC). AM0018: baseline methodology for steam optimization version 03; 2012C [Retrieved Jan 10, 2016 from cdm.unfccc.int/methodologies/DB/D9S0ST4506RVU6JMZKBV9IDK8WFMUP].

United Nations Framework Convention on Climate Change (UNFCCC). AMS-II.C.: demand-side energy efficiency activities for specific technologies version 14.0; 2012C [Retrieved Jan 10, 2016 from cdm.unfccc.int/methodologies/DB/QLHVO5QIRIDVE6092VXPRAG9VZIOZP].

United Nations Framework Convention on Climate Change (UNFCCC). AMS-III.Q.: waste energy recovery version 5.0; 2012C [Retrieved Jan 10, 2016 from cdm.unfccc.int/methodologies/DB/RGPW18XV4FJH1FTTGS2LSD3BWNKNAA].

Worrell E, Price L, Martin N. Energy efficiency and carbon dioxide emissions reduction opportunities in the US iron and steel sector. Energy 2001;26(5):513–36.