Optimizing the Refinery Operational Configuration: Case in Taxation at CO_2 Emission

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Abstract: A refinery is essentially a joint production process system. Due to the complex nature of the process involved, while it converts heavier oils into high quality oil products, fuels and other high value products, it also provides a way to curb carbon dioxide (CO_2) emissions. As refineries are profit-seeking businesses, this paper used linear programming (LP) models to assess the impact of different taxation amounts on CO_2 emissions on a refinery's operational configuration, and energy using strategies for a refining expansion project in Taiwan, and to discover what the carbon price should be in order to justify the required changes. The result reveals the necessity of developing processes, such as the Delayed Coking (DCU) process combined with hydrotreating, to produce high-quality fuels and petrochemical products in the refinery. Our findings indicate that this anticipated expansion plan reduced CO_2 emissions by 4.92%, while obtaining an efficiency of 14.46 USD/ton-CO_2 at a cost of 30 USD/ton-CO_2, and by 10.33% and 25.22% CO_2 emission with efficiency gains of 15.22 and 78.61 USD/ton-CO_2 at a cost of 90 and 180 USD/ton-CO_2, respectively. When emission costs are over 90 USD/ton-CO_2, the refinery opts for liquid petroleum gas (LPG) instead of burning fuel oil, since using hydrogen as a makeup fuel only proves beneficial when the CO_2 emission costs are over 150 USD/ton-CO_2.

Keywords: Crude oil, process, efficiency, fuzzy price, energy-intensive.

1. INTRODUCTION

Since 1946, Taiwan's domestic oil market, along with its attendant exploration, mining, refining, transportation and trading was all monopolized by a state-owned refinery enterprise. However, the government began to liberalize the oil market in 1987 for internationalization and privatizing purposes.

In 1996, the establishment of privately owned and operated refinery enterprises was permitted, giving private firms the right to produce, import/export and market petroleum products. When the privately owned refineries were developed in 2000, the state-owned company's monopoly status in the market was terminated; thus, the duopoly period began. Presently, the state-owned company holds a market share of 70% in the domestic oil market, and privately owned refineries hold 30%.

The budget of the state-owned oil company comes from taxpayers; however, the privately owned oil companies have relatively low production costs compared to state-owned oil company. Based on the relatively low production costs, a private refinery can adopt an oil pricing strategy to increase the market share and revenues in its local marketing [1]. To deal with the excessive production capacity for gasoline and diesel fuel following the liberalization of the domestic market after duopoly marketing began, privately owned oil companies had to evaluate their readjustment and improvement of their refinery configurations to conform to market needs and trends, in order to optimize their oil production and achieve maximum profits.

Refinery configuration involves a series of process units, with crude oil undergoing refining processes to produce available fuels: gasoline, diesel, jet fuel, chemicals-lube oils, solvents, asphalt, etc. The main processing units in a refinery configuration include: distillation, separation, hydrotreating, reforming, cracking and conversion. Different refineries have different configurations comprising different refinery processing units, and this results in different energy consumption aspects among the refineries. Progress in oil refining requires high energy consumption for operations in the refinery processing units. Energy consumption in the refinery processes entails between 7% and 15% of the input from crude oil, and the cost of energy consumption in the refining process normally represents over 50% of the refinery's operational costs [2]. In addition, this high energy consumption leads to high CO_2 emissions. Due to oil refining being one of the industries with the greatest CO_2 emissions, levying a tax on CO_2 emissions for refineries means that oil refineries are now facing another major challenge in attempting to maximize refinery profitability. Furthermore, refineries have to convert heavier oils into high quality oil products, fuels and other high value products with the restricted supply of light crude oil and the rising demand of high quality oil products. This heavier oil conversion makes the refinery configuration more complex and increases both energy consumption and CO_2 emission. However, through the adjustment of the refinery's configuration, during heavier oil conversion, circumstances may permit the optimization of energy consumption and CO_2 emission; this adjustment of configuration for an existing

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refinery may also be done by rearranging the refining operation scheme.

In focusing on curbing CO_2 emissions, most refineries emphasize the actions related to energy efficiency (including heat integration, energy loss control, steam and fuel balancing management, etc), placing them in primary importance while pursuing their desired results. However, room for improvement is narrowing after years of improvement. Since the operational cost of refineries is enhanced in satisfying CO_2 emission targets, the refineries have to find additional ways to curb their carbon emissions. As it is very likely that refineries will continue to face carbon emission restrictions by Taiwan government's taxation, they will have to consider altering their fueling plans and refining configuration to achieve the necessary reduction of carbon emissions. Therefore, an evaluation of the CO_2 taxation required to force change in privately owned refineries' processing strategies is needed, keeping in mind the competitor's advantage of a budget provided by taxpayers.

Refineries can reduce CO_2 emissions in several areas, and the use of the LP model can identify the optimum combination for emission reduction strategies. The areas of reduction for CO_2 emissions are as follows [3]:

(1) Energy efficiency improvements: Improving the efficiency of energy usage is a common practice for most refiners.

(2) Crude substitution: Refinery configuration feeds with heavier or higher sulfur crudes cause higher CO_2 emissions compared to light or lower sulfur crudes.

(3) Fuel substitution.

(4) Hydrogen production.

(5) Residue upgrading.

(6) Carbon capture and sequestration.

As refineries are profit-seeking businesses, this paper intends to explore the impact of taxation on CO_2 emissions on energy using strategies and refining configurations of a private refinery in Taiwan and to discover what the carbon price should be to justify the required changes.

2. LINEAR PROGRAMING ON OPTIMIZATION REFINING MODELS

Petroleum refining is a multiproduct-producing activity which comprises a set of interrelated refining processes. LP is a suitable tool with which to optimize the solution required for the allocation of complex resources, and is widely used in oil production [4], production scheduling [5], production planning of offshore [6], planning refinery operations [7, 8], optimizing for refinery's energy [9] and hydrogen network [10], zero-waste studying [11], as well as completing policy analysis on refinery location [12] and supply chain's study [13]. In addition, LP has also been used to allocate CO_2 emissions [14-16] and joint cost [17] among various refining products.

The impact of a carbon emission tax on refineries is complex; it may influence the operation models of processes, for example catalytic cracking and steam reforming, and can necessitate refinery configuration for an upgrading. There are two areas, besides efficiency improvement and energy integration under a certain blending type of crude to be refined, where it may make sense to minimize total CO_2 emissions: burning low carbon fuels produced during the refining activities, and capturing the CO_2 from the emission points where it is produced in large amounts. Refinery LP is the way to analyze the impact of CO_2 emission costs on refineries for decision making.

A refinery configuration consists of a series of refining units as well as utilities. Different refining units have different characteristics of energy-intensity and CO_2 emission. Configuring certain capacities of refining units can result in typical amounts of CO_2 emission; for example, the catalytic cracking process requires higher fuel consumption and results in a high energy-intensive property, even if it has recovered significant steam during the burning procedure of the catalyst coke. The hydrogen production process is high energy-intensive and also produces a reacted CO_2 byproduct through the shift reaction. Lowering unit capacities of this kind of high energy-intensive process may produce smaller amounts of total CO_2 emissions, an important result when considering CO_2 taxation during programming. Besides, the energy usage also decreases and operational costs can be lowered in this manner.

A refinery LP model has to describe the interactions between the process units, as well as energy consumption and pollution emissions. The objective function used in a refinery LP model can be either to meet a certain market demand of finished products at a minimum cost or to seek maximum profits. A model's main variable is that the mass flows circulate between the process units; this includes the crude oil to be processed, the intermediate products and the final products. For a CO_2 emission-related problem, the constraints taken into account in refinery models include the following:

(1) Material balance equations which are established by the yields of the process units

(2) Quality constraints which express the obligations of intermediate and final products to meet the unit processing specifications

(3) Final products' demand constraints which are to meet a given market demand

(4) Unit capacity constraints which reflect the limitations of capacity of the existing processing units

(5) A CO_2 balance equation which aims to capture all emissions from refinery activities (covers the burning of fuels, hydrogen production and coke burn-off from fluid catalytic cracking)

(6) Petroleum availability equations to meet given process conditions.

Subject to technical and economic constraints, we may now consider a cost function to state the LP model of a refinery in Equation (1):

$$\begin{aligned} & \min \ Z = \sum_{j=1}^{n} c_j x_j \\ & s.t. \ \sum_{j=1}^{n} a_{ij} x_j \geq b_i \qquad (i = 1,2,\ldots,m) \\ & \qquad x_j \geq 0 \qquad (j = 1,2,\ldots,n) \end{aligned} \tag{1}$$

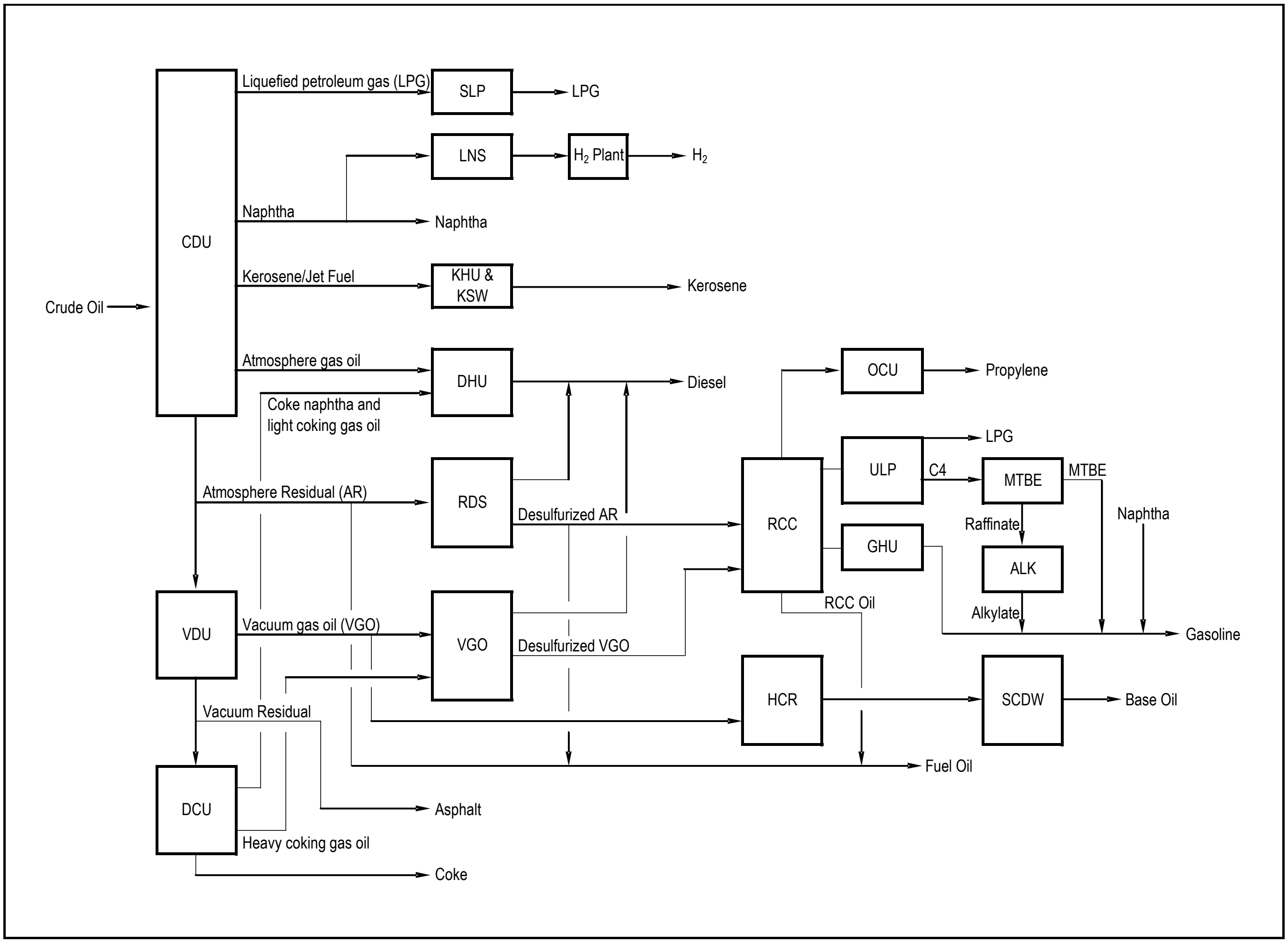

Fig. (1). Simplified scheme of the refining units. Note: Please refer to **APPENDIX** for nomenclature.

The term c is the given vector of acquisition input cost; it includes the cost of crude oils and feedstock, the operating variable cost, exchange cost of finished product and the permit price of CO_2 emission for future years. Term x is the quantity vector of the operation process; term a is the quantity vector of resources consumed; and term b is the vector of quantity of resources available for each process operation.

The LP can be used to evaluate potential CO_2 reduction schemes and how the viability of the schemes varies with emission pricing, in order to identify the optimum reduction level at a certain emission price. Hence, this article uses LP models with consideration of varied price scenarios for carbon emissions, to examine the changes in processing schemes in complex refinery configurations in a privately owned refinery in Taiwan.

3. ESTIMATING CO_2 TAXATION IMPACTS

3.1. Determining the Base Operational Configuration

The production process evaluated at the privately owned refinery consists of 26 refining processes divided into 4 process unit groups: topping distillation process units, refining process units, deep refining process units and petrochemical process units. The topping process units include: a crude distillation unit (CDU) which transfers feed crude oil into naphtha, distillates (kerosene and gas oil), asphalt and gas processing units. Refining and deep refining process units cover: hydrotreating, coking, catalytic and hydrocracking processes; the aim is to transfer distillates and CDU bottom oil into specific product oils, and petrochemical process units; it includes conversion processes that convert refining raffinates into chemicals. The production process, which is presented in simplified form, is illustrated in Fig. (**1**).

There are three trains of CDU in the privately owned refinery, each designed with an operation capacity of 180,000 barrels per day (bpd) to process a total of 540,000 bpd of blended crude oils at present. The atmospheric residues (AR) of two CDU are used for desulfurization and then catalytic cracking for fuel oil production, and one CDU's AR is used for delayed coking and hydrocracking after treatment by two vacuum distillation processes for coke and lube oil production.

The refinery was built to supply enough naphtha for the needs of downstream naphtha cracking and aromatic reforming facilities inside the regional complex, and the refinery is projecting refining capacity expanded to 600,000 bpd of blended crude oils to match the growth in the naphtha oil demand and lower the import ratio of naphtha oils by about 4.9% for satisfying the needs of downstream naphtha crackers and aromatic reformers.

Table 1. Demand of Product Yields (wt% of Crude) Defined in the Model

Refining Products	540,000 barrels/d (wt% of Crude)	600,000 barrels/d (wt% of Crude)
Propylene	3.1 %	3.4 %
LPG	3.7 %	2.1 %
Naphtha	20.4 %	22.1 % (1)
Gasoline	16.7 %	15.3 %
Kerosene	9.7 %	10.3 %
Diesel	30.8 %	31.6 %
Lube Oils	3.0 %	2.5 %
Fuel Oil	1.9 %	1.8 %
Coke	2.7 %	3.6 %

Note: Yield includes unconverted oil of hydrocracker which is as the feed of downstream olefin cracking process.

The refinery also produces fuels for the domestic market, with the surplus aggressively exported. The configuration of the refinery includes the integration of the production of fuels and petrochemicals. In addition, the refinery is projecting modifications to meet governmental regulations on low sulfur content in regard to oil derivate products, and to increase its ratio of heavy-oil conversion for optimized production of high-quality medium and light products. Hence, in order to examine the impact of CO_2 restrictions emissions on the configuration of a modified scheme, we applied possible adjustments to the refining scheme configuration for the expanding project in the LP model, to test the influence of CO_2 taxation, and optimized the expanded scheme after including different CO_2 emission values in the model.

A possible scheme involved integrating the production of high-quality fuels and petrochemicals with the following requirements, while including the taxation of CO_2 emissions:

(1) Naphtha production has to meet the increasing needs of downstream facilities.

(2) Production amounts of propylene have to increase by around 2.4% (to follow the growth rate of domestic needs, on average).

(3) Maximize the output of high-quality fuels.

The products integration scheme aims to produce propylene via an olefin conversion process, and a hydrocracking process is employed for heavy oil conversion and lube oil production. Besides, the residue fluid catalytic cracking (RCC) unit is set in the operation of a propylene mode instead of a gasoline mode for the integration of these products. Table **1** shows the demand scenarios of the overall refining yield defined for the integrated refining configuration.

To achieve the desired product amounts, the refinery has to revamp and redistribute the refining flow scheme and add or expand the units' capacity based on the existing configuration. Table **2** shows the production capacity of the main processing units in the existing refining configuration. During the running of the initial optimization configuration for the expansion project, the refinery had taken into account that operational costs, investments and yield form its data base. Moreover, the price of crude oil and refined products vary and significantly influence the objective function. This led us to adapt fuzzy prices to determine the price of crude oil and oil products used in the LP models, and the models became a fuzzy linear program problem that arose from fuzzy objective function coefficients. The "strong probability factor" was used to combine the fuzzy objective functions [18] incurred by the varied prices. The price of crude oil and the price of product oils taken for the fuzzy models are the monthly prices on average from January 2008 to December 2010.

We initially optimized our base configuration mode, which had no restrictions on CO_2 emissions. The object function to be made for the base configuration mode, subject to constraints, considered the investment cost of the units to be expanded and to be built, the operation costs and the yield of the products under their quality specifications.

Table 2. Operational Capability of Main Units at Existing Refinery Configuration

Units	Capability ($\times 10^3$ t/yr)
Crude distillation	24,810
Vacuum Distillation	7,034
Residue Desulfurization	8,519
Residue Catalytic Cracking	8,203
Olefin Conversion to propylene	916
Alkylation	584
MTBE Production	319
Hydrocracking	1,335
Diesel Hydrotreating	5,761
Delayed Coking	1,988
Vacuum Gas Oil Hydrotreating	2,541
Selective Catalytic Dewaxing	704

Before proceeding further, we considered the refinery optimization model in which the refinery processes blended crude oil with six different types of crude oils (Arabia light, Arabia heavy, OMA, KEC, BLT and IH) to produce two

Table 3. Programming Results at Different CO_2 Taxation

US$/t CO_2	0	30	60	90	120	150	180
CO_2 Emission, $\times 10^3$ t/yr	9,469	9,003	8,941	8,491	8,326	7,473	7,081
Energy consumption							
Total, $\times 10^3$ MMkcal/yr	24,159	22,626	22,838	22,172	21,600	19,586	18,534
Fuel, %	33.14	34.73	34.16	37.91	33.91	36.77	42.19
Steam, %	36.70	35.22	34.80	32.19	32.41	27.58	23.12
Power, %	8.30	6.97	8.62	8.74	8.32	9.05	9.14
RCC Coke, %	21.86	23.08	22.42	21.16	25.36	26.60	25.55
Total, %	100	100	100	100	100	100	100
Saving, %	Base	6.34	5.47	8.22	10.59	18.93	23.28
Saving of manufacturing Cost							
MMUS$/yr	Base	123.00	110.46	56.06	198.72	329.65	312.91
%	Base	8.63	7.75	3.93	13.94	23.12	21.95
Unit Capacity, $\times 10^3$ t/yr							
CDU	27,344	27,344	27,344	27,344	27,344	27,344	27,344
RDS	9,390	8,627	8,950	7,847	9,301	8,649	7,850
RCC	8,280	8,188	8,029	7,358	8,590	8,170	7,426
VDU	6,292	6,100	5,957	6,903	6,692	6,037	6,836
DCU	2,977	3,472	3,213	3,618	2,181	3,305	3,534
DHU	7,400	8,214	7,966	5,563	7,501	8,028	5,959
VGO	2,241	2,705	2,409	929	2,553	3,105	938
OCU	947	572	577	517	1,024	379	345
HCR	1,250	1,107	1,167	6,275	1,305	1,094	4,572
GHU	3,510	3,272	3,161	2,933	1,870	1,716	1,562
SCDW	771	684	721	686	815	732	736
KSW	2,632	2,591	2,612	2,591	1,927	2,468	2,430
ALK	1,003	1,085	1,087	983	581	940	854
MTBE	664	1,250	1,240	1,126	452	994	903

main oil products: gasoline and diesel, with naphtha and propylene, as mentioned above. The goal is to satisfy the production target for each oil and petrochemical product at minimum cost, subject to the fuzzy price of crude oils. The result of the base configuration mode is limited to 600,000 bpd of blending crude with blended characters of an API grade of 29.8 and a sulfur content of 2.44. The yield of the main process units used in the models is as per the data base of the process units of the refinery, and the result of the base configuration mode is shown in Table **3** (case of CO_2 priced at 0 US$/t CO_2). The optimized scheme sends 56.8% of the AR combined with part of the vacuum residue (VR) to the residue desulfurization (RDS) process, and the desulfurized AR is then sent to the residue catalytic cracking for gasoline production. On the other hand, the remaining 43.2% of the AR is sent to the vacuum distillation, the heavy vacuum gas oil is sent to the hydrocracking process for lube oil production and the VR is sent to the DCU. As per this optimized scheme, the CO_2 emission is on the level of 0.35 kg CO_2/ton of crude, and the total production cost inside the battery limit of the optimized refining scheme is 641 USD/ton of crude.

3.2. Carbon Emission Tax Scenario

To evaluate the impact of CO_2 emission charges, the models considered CO_2 taxing at different levels for optimization, as carbon tax is expected to be the most efficient approach to reduce carbon emissions. According to former research [19, 20] the tax rates of 30 USD/t-CO_2, 60 USD/t-CO_2, 90 USD/t-CO_2, 120 USD/t-CO_2, 150 USD/t-CO_2 and 180 USD/t-CO_2 were applied. The lower rate was considered to be higher than the price trend in the European carbon market under pressure from climate change, and the higher rate added a gap rate at 150 USD/t-CO_2, which roughly corresponds to the non-compliance fine to Phase II of the European Union Emission Trading Scheme ($Euro 100/t-$CO_2$). It was also assumed that the carbon tax rate would gradually be increased over time.

3.3. Determining the Impact of CO_2 Taxation

Besides CO_2 emission charges, the model must be re-optimized under the emission tax. While re-simulating the impact, CO_2 emission costs were included in the objective function, and the remaining constraints were kept the same to evaluate the possible changes of operational capacities of refining units and energy using strategies (the distribution of CO_2 emissions). A balanced equation of CO_2 emissions was also needed to signify the whole CO_2 emissions in refining activities.

The emission cost was assumed to be equal to the total quantities released multiplied by the price of an emission permit. The emission permit was the total emission amount before expansion. It was assumed that the break-even point was at a marginal cost of CO_2 reduction equal to the emission tax, and that the refinery owner would pay the emission tax until the tax exceeded the marginal cost of CO_2 reduction.

Three main emission sources of CO_2 have been covered in simulations during modeling CO_2 emissions in the LP:

(1) Fuel for process fluids' heating, steam rising and power generation

(2) Hydrogen production

(3) Coke from catalytic cracker burn-off

The burning fuels (liquefied petroleum gas, refining heavy oil) contributing to CO_2 emissions were generated from the refinery itself. After establishing the carbon content of any fuels used: fuel gas, liquefied fuels, coke from the catalytic cracker and hydrogen, each was assigned a specific CO_2 emission coefficient; we assumed that the CO_2 content of refinery fuels was proportional to their quantities. Energy consumption of process units was predicted by such factors as: throughput, feed or product qualities, conversion levels, etc. Moreover, a constraint of CO_2 emission amount had to be addressed to realize a possible reduction and not exceed the amount from the current operation level.

4. RESULTS

4.1. Refining Scheme Simulated for Operation

Simulation results help management to choose the expansion scheme with the most beneficial operation flexibility when CO_2 emissions are taxed. Table **3** shows simulation results under varying carbon emission taxes. In this table, we see that in the case of CO_2 taxation being increased from 30 USD/ton to 180 USD/ton, carbon emissions were reduced from the original 9.4 million tons per year to 7.08 million tons per year, which is a 25.22% reduction.

Due to the additional CO_2 pricing costs, the simulation optimizes the use of energy and unit operation capacities to reduce operational costs while reaching the marginal cost of CO_2 reduction.

The refinery has two vacuum distillation units (VDU) in operation as mentioned above. Based on the feed properties, one VDU's VR was equipped with a higher con carbon character, and we had to draw a main column bottom (MCB) of RCC to adjust it while feeding to DCU. When the CO_2 tax is increased, the refinery configuration shifts to a low carbon emission scheme, as Table **3** (unit capacities) indicates. As can be seen, when CO_2 emissions are taxed, the refinery will route more VR and MCB to DCU, which is a mid-energy-intensive process for gas oil production, and the refinery increases the capacity of diesel hydrotreating unit (DHU) and vacuum gas oil hydrotreating unit (VGO), which are lower energy-intensive processes for processing the surplus light and heavy coke gas oil individually. These results show that DCU products are unstable and have to be hydrotreated for stabilization. Fig. (**2**) shows the trends of operational capacities of DCU, DHU and VGO versus the charges for CO_2 emissions. With more VR feeds to DCU, RDS's and RCC's operation capacities, which are mid- and higher-energy-intensive processes, respectively, were decreased accordingly. These operation configurations, compared to a no carbon charge case, will reduce the total energy consumption by at least 5.47%; 3.93~23.12% of manufacturing costs can also be reduced.

In the results of pricing case 30, 60 and 90 USD/t-CO_2, the simulation emphasizes the necessity of making processes, such as DCU combined with hydrotreating processes (DHU, VGO), reach high-quality fuels and petrochemical production in the refinery. Compared to a base configuration mode, VR fed to RDS was decreased and more additional AR was processed by RDS to make up for the decrease, resulting in lower RDS operation capacity. Furthermore, the operation capacity of higher energy-intensive processes, such as RCC, gasoline hydrotreating unit (GHU) and olefin conversion unit (OCU), tended to decline. The processing capacity of higher hydrogen consumption processes, such as HCR, for lowering the total hydrogen consumption, also tended to decline because hydrogen production is a significantly high energy-intensive process.

Two different results were obtained during the program simulations. First, differences appeared in the pricing cases of 90 USD/t-CO_2 and 180 USD/t-CO_2 when expansion of mild gas oil hydrocracking was put in operation. In these cases, the simulation resulted in routing additional AR to VDU (around 10% more), more high con carbon VR and MCB drawn to the DCU (around 20% additional), and a decrease of one half of VGO's capacity for routing vacuum gas oil (from VDU) and heavy coke gas oil (from DCU) to expand the mild hydrocracking process, which had 2.6~3.5 times more operation capacity than the existing one. In addition, RDS was fed only by AR with less operation capacity. These optimized operational configurations reduced 10.33% in emitted CO_2 by saving 8.22% in energy consumption in the case of 90 USD/t-CO_2, and reduced 25.22% in emitted CO_2 by saving 23.28% in energy consumption. In addition, 3.93% and 21.95% of manufacturing costs for cases of 90 and 180 USD/t-CO_2 were also abated.

Second, change was observed for the case of 120 USD/t-CO_2. The simulation result in this case showed that the heavy vacuum gas oil produced from the 1st VDU was combined with AR for feeding to the 2nd VDU, and the VR stream produced from the 2nd VDU was then fed to the RDS series to go for desulfurization and catalytic cracking for fuel oil production. In this case, after making up by VR, AR for RDS serial processes was slightly reduced and for VDU was

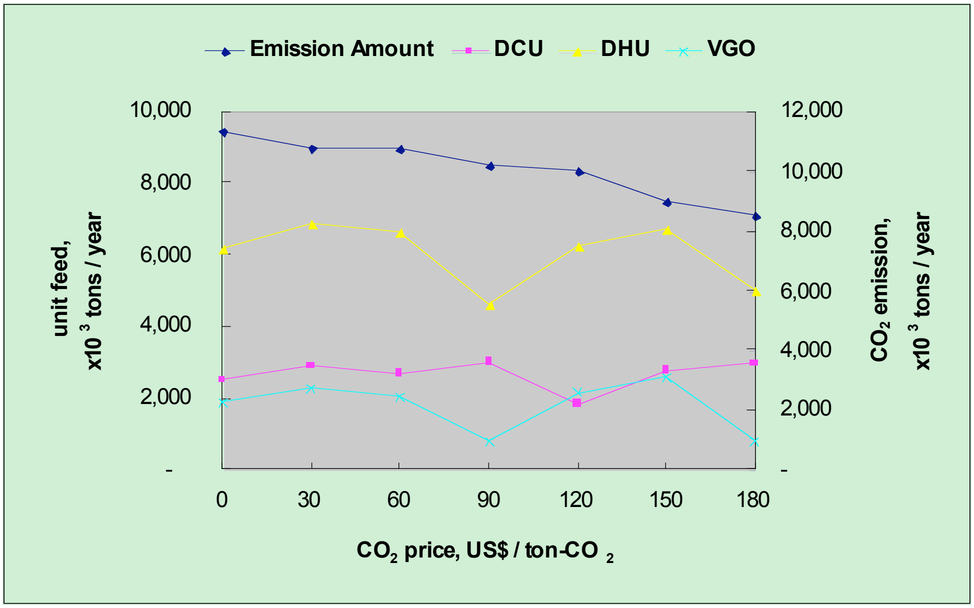

Fig. (2). Unit operation capacities with CO_2 emissions at different CO_2 taxation.

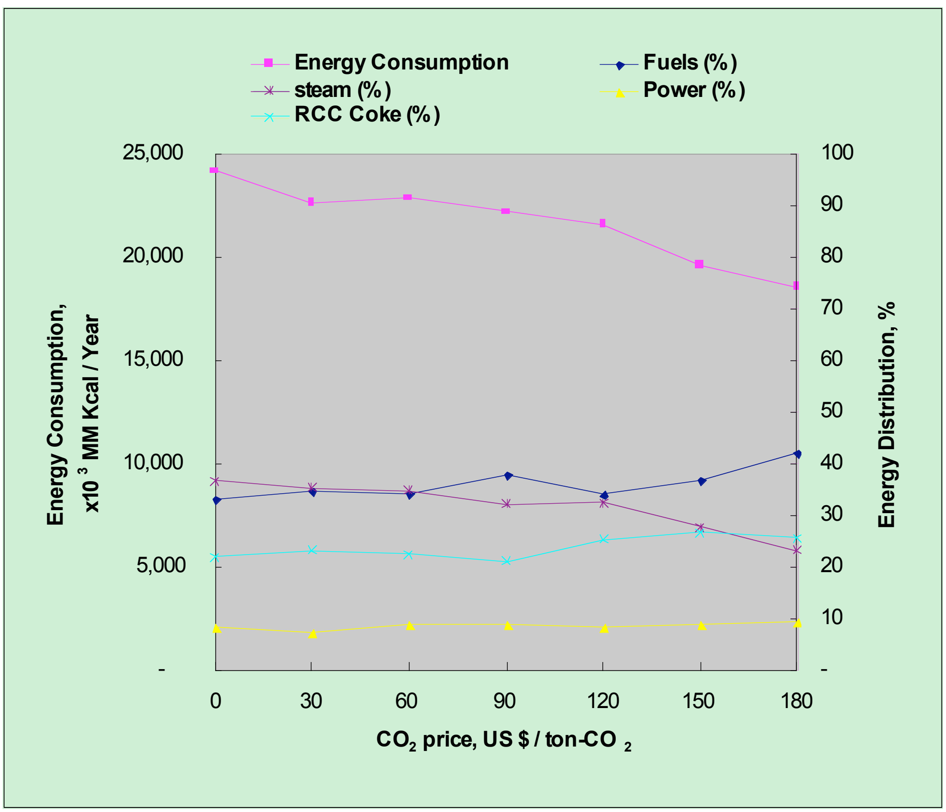

Fig. (3). Energy consumptions and distributions at different CO_2 taxation.

increased; then the VGO's and RCC's operation capacities were increased. On the other hand, the processing capacity of high energy-intensive processes, such as the GHU, alkylation unit and hydrogen plant, tended to decline a lot to lower the total CO_2 emission. This operational configuration reduced 12.07% of the emitted CO_2, saving 10.59% in energy consumption and 13.94% of the manufacturing costs.

4.2. Fuel Arrangement

When simulation changes the refining scheme, the distribution of energy consumption is changed too. Fig. (**3**) shows the changes of distribution of energy consumption with different taxation rates on CO_2 emissions.

Besides the changes in operation configuration, the simulation shows that it is better for the refinery to switch

Table 4. Results for Hydrogen Makeup Fuelling at Different CO_2 Taxation

US$/t CO_2	30	60	90	120	150	180
CO_2 Emission, $\times 10^3$ t/yr	8,386	8,260	7,737	7,426	6,739	6,155
Emission Reduction, %	11.44	12.77	18.30	21.57	28.84	34.99
Fuel consumption						
Total, $\times 10^3$ MMkcal/yr	8,500	8,509	9,324	8,422	8,098	9,409
H_2 for fuel, $\times 10^3$ MMkcal/yr	92.20	101.72	132.10	157.72	128.75	162.13
Saving of manufacturing Costs						
MMUS$/yr	-15.34	-42.16	-136.06	-30.66	142.40	77.12
%	8.63	7.75	3.93	13.94	23.12	21.95

Table 5. Results of Emission Reduction

Makeup Fuel	Fuel Oil		LPG				H_2	
US$/t CO_2	30	60	90	120	150	180	150	180
Emission Reduction								
$\times 10^3$ t/yr	466	528	978	1,143	1,996	2,388	2,730	3,314
%	4.92	5.57	10.33	12.07	21.08	25.22	28.84	34.99
Cost of Break-even Point, US$/t CO_2	15.54	44.99	74.78	84.37	83.41	101.39	95.92	77.82
Efficiency Gain								
US$/t CO_2	14.46	15.01	15.22	35.63	66.59	78.61	54.08	102.18
% of CO_2 price	48.21	25.01	16.91	29.70	44.39	43.67	38.97	39.61

the refining fuel (except from refinery gas) from fuel oil to LPG, self-produced to reduce emission costs when the charge for CO_2 emissions is over 90 USD/ton, since LPG has a lower CO_2 emission factor than the refinery fuel oil does.

Based on the obtained results, a hydrogen fuelling case has been simulated. In this case, we utilized product hydrogen as the makeup fuel, and applied a unit to capture and sequester the high concentration CO_2 emitted from hydrogen plants, under a full range of CO_2 taxation. While adding hydrogen into fuel is an effective way to reduce CO_2 emissions, in reality, the hydrogen production process can also produce a significant amount of CO_2 as a byproduct in an exhaust stream with relatively high concentration. So we see that hydrogen plants are major CO_2 emission refinery sources that allow a single stream source to be a target for CO_2 capture and storage (CCS), and it is quite natural to join a CCS unit with a hydrogen production process in this case.

In this case the source of CO_2 capturing is from the CO_2 removal section upstream of the pressure swing adsorption (PSA) when hydrogen is added to the fuel system. The results reveal that using hydrogen as a makeup fuel increases the reduction of total CO_2 emissions from 11.44% at a charge of 30 USD/ton to 34.99% at a charge of 180 USD/ton. On the other hand, the manufacturing cost is not beneficial until the CO_2 emission charge is over 150 USD/ton, and the savings are much lower than when adding LPG to the fuel system. The results are presented in Table **4**.

As mentioned in 3.2, the break-even point is at the marginal cost of CO_2 reduction being equal to the emission tax, and the refinery owner will accept paying the emission tax until the tax exceeds the marginal cost of CO_2 reduction. Table **5** shows the figures of CO_2 pricing, emission reductions and costs at a break-even point for CO_2 when adding fuel oil, LPG and hydrogen to the fueling system. Once a CO_2 tax of 30 USD/ton-CO_2 is charged, the refinery starts to reduce its emissions only by changing the operation configuration (scheme) of refining without changing to a low carbon fuel, and the scheme change can only reduce 4.92% of CO_2 emissions as well as realize an efficiency gain of 14.46 USD/ton, which equals 48.21% of the CO_2 taxation costs in this circumstance. After charging a price of 90 USD/ton, the refinery will opt to make up LPG to further decrease CO_2 emissions to 10.33% to gain the same extent of efficiency in relation to cost.

If adding hydrogen to the fuel is considered, there is no efficiency gain for the refinery until a cost of 150 USD/ton-CO_2 is charged. Based on the results, the refinery significantly reduces its CO_2 emissions by 28.84% at this price, and the efficiency gain in relation to this CO_2 price is 54.08 USD/ton-CO_2, which equals 38.97% of the tax on CO_2 emissions.

5. CONCLUSIONS

The impact of a carbon emissions tax on the expansion refinery configuration of an existing refinery has been investigated herein using a linear program; the configuration was optimized by using different taxation rates for CO_2 emissions.

Simulation for the expansion of 600,000 bpd throughput of CDU requires existing units' revamping of their operational capacities. The results show that different scenarios for carbon emission costs require different extents of revamping of units' capacities. This reveals that changing refinery operation configurations can create opportunities for less carbon emissions, to a certain extent. After comparing the capabilities of existing process units inside the refinery, it can be seen that revamping based on the price scenario of 90 USD/ton-CO_2 can include the abilities of operation configurations of all simulated carbon emission prices to fit the impact of carbon tax and the growth of naphtha oil demand inside the complex. The results indicate the following:

(1) Increased HCR operational capacity combined with decreased RDS, RCC and hydrotreating processes' operational capacity is the way to reach high-quality fuels and petrochemical products at higher taxation amounts of CO_2 emission, and drawing VR to increase DCU and hydrotreating processes' capacities with decreasing RDS's capacity is the way to reach high-quality diesel productions at lower taxation amounts of CO_2 emission in the refinery.

(2) Once a CO_2 tax of 30 USD/ton-CO_2 is charged, the refinery can reduce 4.92% of CO_2 emissions only by changing the operation scheme of refining configuration, without changing to a low carbon fuel.

(3) When the charging price is over 90 USD/ton-CO_2, the refinery opts for liquid petroleum gas instead of fuel oil burning since using hydrogen as a makeup fuel is not beneficial until the CO_2 emission costs are over 150 USD/ton-CO_2.

APPENDIX

NOMENCLATURE

ALK	=	Alkylation Unit
CDU	=	Crude Distillation Unit
DCU	=	Delayed Coking Unit
DHU	=	Diesel Hydrotreating Unit
GHU	=	Gasoline Hydrotreating Unit
HCR	=	Hydrocracking Unit
KHU	=	Kerosene Hydrotreating Unit
KSW	=	Kerosene Sweetening Unit
LNS	=	Light Naphtha Sweetening Unit
MTBE	=	MTBE Production Unit
OCU	=	Olefin Conversion to propylene Unit
RCC	=	Residue Catalytic Cracking Unit
RDS	=	Residue Desulfurization Unit
SCDW	=	Selective Catalytic Dewaxing Unit
SLP	=	Saturated LPG Sweetening Unit
ULP	=	Unsaturated LPG Sweetening Unit
VDU	=	Vacuum Distillation Unit
VGO	=	Vacuum Gas Oil Hydrotreating Unit

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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