Journal of Engineering Science and Technology
Vol. 12, No. 12 (2017) 3329 - 3343

ECONOMIC COMPARATIVE EVALUATION OF COMBINATION OF ACTIVATED CARBON GENERATION AND SPENT ACTIVATED CARBON REGENERATION PLANTS

TINNABHOP SANTADKHA, WANWISA SKOLPAP*

Department of Chemical Engineering, Faculty of Engineering,
Thammasat University Pathumthani, Thailand 12120
*Corresponding Author: swanwisa@engr.tu.ac.th

Abstract

The purpose of this study was to investigate the maximum annual profit of proposed three project plants as follows: (i) a generation process of activated carbon (AC) prepared from coconut shells; (ii) a regeneration process of spent AC obtained from petrochemical industries; and (iii) a project combined the AC generation process with the regeneration process. The maximum annual profit obtained from the sole regeneration plant was about 1.2- and 15.4- fold higher than that obtained from the integrated and the generation plants, respectively. The sensitivity of selected variables to net present value (NPV), AC sales price was the most sensitive to NPV while fixed costs of generation and regeneration, and variable cost of regeneration were the least sensitive to NPV. Based on the optimal results of each project plant, the economic indicators namely NPV, return on investment (ROI), internal rate of return (IRR), and simple payback period (SPP) were determined. Applying a rule of thumb of 12% IRR and 7-year SPP, the AC sales prices for the generation, regeneration, and integrated plants were 674.31, 514.66 and 536.66 USD/ton of product, respectively. The economic analysis suggested that the sole regeneration project yields more profitable.

Keywords: Activated carbon, Generation plant, Profit optimization, Regeneration plant, Spent activated carbon.

1. Introduction

Activated Carbon (AC), carbonaceous sorbent, is prepared from plentiful available cellulose-based biomass waste, i.e., coconut shell, pecan shell, peat, and

Nomenclatures

C_G	Generation cost (Eq. 6), USD/period
C_I	Inventory cost (Eq. 8), USD/period
C_P	Purchase cost of virgin AC (Eq. 9), USD/period
C_R	Regeneration cost of spent AC (Eq. 7), USD/period
D	Demand of product {1,800, 3,500, 4,200}, ton /period
f_G	Fixed cost of generation process {98, 645}, USD/period
f_R	Fixed cost of regeneration process {98, 645}, USD/period
I_t	Inventory of product, ton/period
p	Selling price of AC per unit {114.29}, USD/ton
q	Inventory cost per unit {5.71}, USD/ton
r	Purchasing rate of virgin AC {828.57}, USD/ton
v_G	Variable cost of generation process {318.29}, USD/ton
v_R	Variable cost of regeneration process {282.86}, USD/ton
X_t	Coconut shell supply rate, ton/period
Y_t	Spent AC amount {950, 1,540, 1,740}, ton/period
$Z_{1,t}$	Regenerated AC amount, ton/period
$Z_{2,t}$	Purchase of virgin AC amount, ton/period
$Z_{3,t}$	AC amount taken out of inventory, ton/period
$Z_{4,t}$	Usable amount of AC generated, ton/period

Greek Symbols

α	Yield of generated AC {0.4}, ton product/ton coconut shell
β	Yield of regenerable spent AC {0.7}, ton product/ton spent AC
δ	Discount rate {7.5}, % per annum
γ	Waste charcoal from generation {0.6}, ton waste charcoal/ton coconut shell
π	Profit, USD/period

Abbreviations

max	Maximum
t	Time index, four-month period {Feb-May, June-Sept, Oct-Jan}

bamboo cane. AC is widely used as for removal of colour, odours, dissolved organic chemicals, and metal ions in many industries such as foods and beverages, petrochemicals and textile. Mostly, the AC applied in petrochemical industry is prepared from coconut shell containing carbon content more than 20% wt [1]. Coconut shell, an abundant domestic agricultural waste, is the most preferable raw material for preparation of charcoal. Further activation of charcoal by either thermal or chemical treatment enhances its adsorption properties resulting in activated carbon. In the thermal activation, a raw material is first carbonized to increase its carbon content and lower its volatile matter content and then activated with oxidizing gas such as water vapour and CO_2 to develop internal porosity by a water-gas reaction. The production cost of steam-activated carbon was lower than that of acid-activated carbon [2]. On the other hand, the

AC preparation by the chemical activation with an ionic reagent, i.e., zinc chloride and phosphoric acid, is operated at lower temperature than thermal activation. Moreover, the production cost of steam-activated carbon prepared from pecan shells was 6% higher than that of acid-activated carbon [2]. Given annual shell input and desired AC throughput are required to minimize production cost in a suitable size of process equipment [2].

The consumption of activated carbons was continuously increasing in the world, whereas the land available for plantation is limited causing the shortage of raw materials supply. Due to the increase of fresh coconut and versatile applications of coconut shell, the quantity of coconut shell for activated carbon is limited. Thus, regeneration process of spent activated carbon, one of sustainable waste management techniques, offers advantages in the aspect of economics, environmental, and energy utilization [3, 4]. There are several regeneration methods such as thermal, chemical, wet air oxidation, solvent extraction and electrochemical regenerations.

The selection criterion of regeneration technique depends on the characteristics of the base material, the activation process, and the type of adsorbate [5]. Chemical regeneration is a possible in situ process, in which adsorbates are removed by reacting with selected chemical reagents. The drawbacks of chemical regeneration are expensive chemical reagents, environmental pollution from hazardous chemicals and partial regeneration. Wet air oxidation uses molecular oxygen as an oxidant at temperatures in a range of 125 and 320°C and pressures in a range of 0.5 and 20.3 MPa [6]. During the wet air oxidation the surface oxidation and the formation of carbon-oxygen complexes on the surface of the carbon could cause the loss of adsorption capacity [7]. Different solvents for the regeneration of exhausted AC, i.e., subcritical water and supercritical CO_2, are introduced through a bed of spent AC to dissolve the adsorbate. A major advantage of supercritical CO_2 is its low critical temperature of 31.06°C and critical pressure of 7.38 MPa [8]. Recently, microwave assisted regeneration is a potential method for high quality of the regenerated AC and reduction of regeneration period. Thermal regeneration comprises three steps such as drying, pyrolysis of adsorbates and reactivation by oxidizing the pyrolysed adsorbate residues. A variety of activating agents such as steam, CO_2, or inert gas is added to the thermal regeneration process for removal of adsorbates causing the carbon weight loss; which in turn, the loss of adsorption capacity is observed. The quality and surface area of AC have direct effects on its selling price [2]. However, thermal regeneration is currently the most widely used regeneration technique.

In this study, the maximum of annual profit was determined for proposed three project plants such as thermal coconut shell-based AC generation, thermal regeneration plant of spent AC obtained from petrochemical manufacturers, and the integrated plants of both generation and regeneration processes. Based on the individual optimal annual profit of each case, economic criteria namely return on investment (ROI), net present value (NPV), internal rate of return (IRR) and simple payback period (SPP) are calculated to make the final decision on investment [9, 10]. Moreover, the sensitivity of NPV to changes in optimization model variables will be analysed.

2. Materials and Methods

2.1. Generation and regeneration plants

Data collection costs in one of existing generation plants of coconut shell-based AC and one of regeneration plants of exhausted AC obtained from petrochemical industries in Rayong, Thailand is shown in Table 1. In the studied plant, rotary kilns are applied for thermal activation of charcoal and regeneration of exhausted AC. The thermal regeneration method is carried out in a rotary kiln consisting of two main processes such as heating of the solid raw material and maintaining the reductive environmental gas [5]. The reductive environment is associated with a water-gas reaction, endothermic reaction, producing hydrogen during 850-1,100 °C. Then the optimization problem was formulated to determine the maximum annual profit of the sole AC generation, the sole regeneration, and integrated plants. After the maximum annual profit was determined, the economic indices as a function of product selling price for making decisions on investment were calculated.

2.2. Methodology

Figure 1 illustrates demand and supply data of generated and regenerated AC for three studied cases. The spent AC was the only supply for the sole regeneration case as shown in Fig. 1 (top, dashed line). Moreover, the demand of the sole regeneration plant consists of three major sources as follows: (i) the direct sales of regenerated spent AC (Z_1), (ii) the purchase of virgin AC as a replacement of non-regenerable AC and waste charcoal (Z_2), and (iii) the AC amount taken out of inventory (Z_3). For the sole generation plant a usable amount of generated coconut shell-based AC (Z_4) was an additional supply of the product as shown in Fig. 1 (bottom, dashed line). The yields of prepared AC and that of regenerable exhausted AC from the studied plant were 40 and 70 %wt, respectively. The optimal and economic feasibility results of three studied cases were estimated.

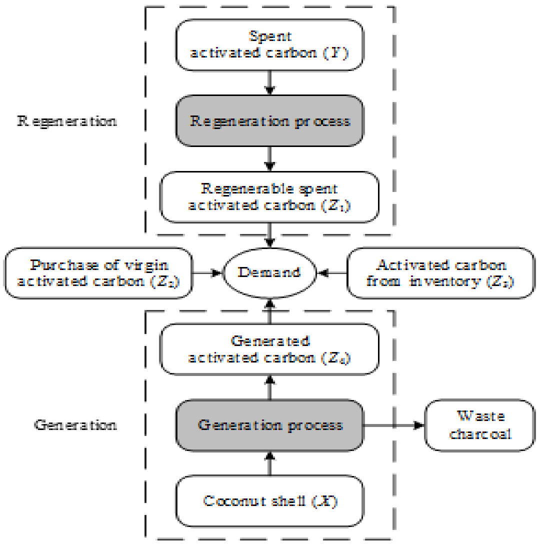

Fig. 1. Scheme of activated carbon demand of the sole generation, sole regeneration and integrated plants.

2.3. Cost information

A summary of the cost data collected from one of generation plants of coconut shell-based AC and one of regeneration plants of spent AC from petrochemical industries in Rayong, Thailand is shown in Table 1 [11].

Table 1. Production cost breakdown and its application in generation and regeneration plant.

No.	Item	Calculation factor	Cost of generation and regeneration cases (USD)	Cost of integrated case (USD)
1	**Land**	4 acres×14,285 USD and other land adjustment.	257,143	257,143
2	**Machines and equipment cost**	Based on production requirement.	1,301,429	2,602,857
3	**Office building construction**	343 USD per square metre × 400 square metre and other interior.	200,000	200,000
4	**Plant construction**	229USD per square metre × 2,000 square metre.	457,143	594,286
5	**Computers and office materials**	IT equipment, computer, printer, copier, scanner and other stationary.	42,857	57,143
6	**Vehicles and assets**	Trucks, pick up car and containers.	371,429	428,571
7	**Utility construction**	Underground water supply, water supply, electricity and gas supply.	666,966	801,342
8	**Cash flow**	Purchasing cost for operation plant and marketing cost.	285,714	857,143
9	**Transportation and installation**	Labor cost, machines and equipment for installation works, import cost.	285,714	571,429
10	**Commissioning and consulting**	Trial run process cost and consultant fees.	428,571	714,286
11	**Expenses before operation**	Government and environmental impact assessment fees.	142,857	200,000
12	**Insurance**	Vehicle, building, plant, Machines and equipment insurances.	114,286	228,571
13	**Salary**	Labor for operation, engineering, R&D, QA, finance, accounting and HR.	135,457	216,229
			4,689,566	7,729,000

3. Problem Statement

The following model assumptions are considered for model formulation of this study.

- Each year was divided into three time periods depending on availability period of coconut shells such as February-May, June-September and October-January.
- The maximum available budget for spending was 2.86 million USD.
- The initial inventory capacity of AC was 1,000 ton.
- The quality of AC produced from generation and regeneration processes were comparable.

The objective function of the optimization problem was the discounted annual profit of regeneration process. The decision variables were coconut shell supply rate (X), regenerated AC amount (Z_1), purchase of virgin AC amount (Z_2), AC amount taken out of inventory (Z_3), generated AC amount (Z_4) and inventory AC amount (I). Parameters used in the problem formulation are illustrated in the nomenclature. The linear-programming optimization model was expressed as follows:

Objective function: Annual profit

$$\underset{X_t\ Z_{1,t}\ Z_{2,t}\ I_t}{\text{Max}} \quad \sum\nolimits_t \pi_t \big/ (1+\delta)^{t-1} \tag{1}$$

Set of constraints:

- Mass balance of generation process for usable AC:

During activation process, charcoal cannot be completely activated. The $\gamma{\cdot}\alpha{\cdot}X_t$ term represents an amount of waste charcoal produced. Thus, the amount of AC produced from coconut shells (Z_4) can be estimated by Eq. (2).

$$Z_{4,t} = (1-\gamma)\alpha X_t \tag{2}$$

- Mass balance of regeneration process:

After spent AC is regenerated, the amount of regenerable AC (Z_1) can be estimated by Eq. (3).

$$Z_{1,t} = \beta Y_t \tag{3}$$

- Mass balance of production:

The demand of AC for each period (D_t) satisfies the amount of AC produced from generation ($Z_{4,t}$) and regeneration process ($Z_{1,t}$), that of purchased virgin AC ($Z_{2,t}$), and that of AC taken out of storage ($Z_{3,t}$).

$$D_t = Z_{1,t} + Z_{2,t} + Z_{3,t} + Z_{4,t} \tag{4}$$

- Mass balance of inventory:

Similar to the calculation of mass balance of production, the quantity of AC held in the warehouse for current time period (I_t) is the excess AC amount from production and from inventory of previous period (I_{t-1}) to prevent inventory shortage [12].

$$I_t = I_{t-1} + Z_{1,t} + Z_{2,t} + Z_{4,t} - D_t \tag{5}$$

- Total cost of generation of AC:

The fixed (f_G) and variable cost (v_G) of generation of usable AC prepared from coconut shells are used in calculating the total production costs of generation and integrated plants as follows:

$$C_{G,t} = f_G + v_G \left(Z_{4,t} + \gamma \alpha X_t \right) \tag{6}$$

- Total cost of regeneration of spent AC:

In a similar vein, the total cost of regeneration of spent AC for regeneration and integrated plants is calculated from its fixed (f_R) and variable costs (v_R).

$$C_{R,t} = f_R + v_R Z_{1,t} \tag{7}$$

- Cost of inventory:

The cost of AC inventory held in the warehouse can be estimated by Eq. (8).

$$C_{I,t} = qI_t \tag{8}$$

- Purchase cost of virgin AC:

In a case of less production than purchase order, the virgin AC is necessarily purchased. It is noted that the purchase cost of virgin AC is more expensive than the selling price of AC as shown in nomenclature. The selling rate of AC is the price for both AC prepared from coconut shells and AC regenerated from spent AC, whereas the purchase cost of virgin AC is derived from procurement outsourcing.

$$C_{P,t} = rZ_{2,t} \tag{9}$$

- Discounted profit:

The annual profit is calculated based on the discount rate of 7.5% per annum.

$$\pi_t = pD_t - C_{G,t} - C_{R,t} - C_{I,t} - C_{P,t} \qquad \forall t \tag{10}$$

- Budget limit:

The total cost of generation, regeneration, inventory, and procurement outsourcing cannot be exceeded the available budget.

$$C_{G,t} + C_{R,t} + C_{I,t} + C_{P,t} \le C^{\max} \qquad \forall t \tag{11}$$

- Generation plant capacity limit:

The maximum generation plant capacity is 3,000 ton/period.

$$0 \le Z_{4,t} \le Z_4^{\max} \qquad \forall t \tag{12}$$

- Regeneration plant capacity limit:

The maximum regeneration plant capacity is 3,000 ton/period.

$$0 \le Z_{1,t} \le Z_1^{\max} \qquad \forall t \tag{13}$$

- Purchase amount limit:

The maximum purchase amount of virgin AC is 3,000 ton/period.

$$0 \le Z_{2,t} \le Z_2^{\max} \qquad \forall t \tag{14}$$

The maximum AC amount taken out of inventory can be expressed as:

$$0 \le Z_{3,t} \le I_{t-1} \qquad \forall t \qquad (15)$$

- Inventory capacity limit:

The inventory capacity is limited by the warehouse capacity of 6,500 ton/period.

$$0 \le I_t \le I^{\max} \qquad \forall t \qquad (16)$$

- Initial inventory quantity:

The initial inventory is set as 1,000 ton of AC.

$$I_{t=1} = 1,000 \qquad (17)$$

The linear-programming optimization problem was solved by using GAMS/CPLEX [13]. The optimization result is shown in Table 2.

Table 2. Results of optimization model.

Parameter	Feb-May			Jun-Sep			Oct-Jan		
	G	**R**	**G&R**	**G**	**R**	**G&R**	**G**	**R**	**G&R**
X **(ton/period)**	3,200	-	852.5	4,800	-	4,800	9,600	-	9,600
Z_1 **(ton/period)**	-	663.6	663.6	-	1,078	1,078	-	1,217	1,217
Z_2 **(ton/period)**	288	136.4	0	2,537	1,492	777	1,859	2,913	1,324
Z_3 **(ton/period)**	1,000	1,000	1,000	195.4	930.1	877.3	804.6	69.88	122.7
Z_4 **(ton/period)**	512	-	136.4	768	-	768	1,536	-	1,536
C_G **(million USD/period)**	0.506	-	0.206	0.706	-	0.706	1.317	-	1.317
C_I **(USD/period)**	5,714	5,714	5,714	4,571	400	714	0	0	0
C_P **(million USD/period)**	0.239	0.113	0.192	2.102	1.236	0.644	1.541	2.413	1.097
C_R **(million USD/period)**	-	0.297	0.297	-	0.404	0.404	-	0.444	0.444

G, R and G&R denote generation, regeneration and integrated plants, respectively.

– denotes non-existence of parameter in the corresponding optimization model.

4. Results and Discussion

4.1. Results of profit optimization

The annual profits of studied regeneration project mainly calculated from the direct sales of generated AC and regenerated spent AC, the purchase of virgin AC for non-regenerated AC, and the inventory of product. The calculation was based on the generation plant capacity of 12 tons per day, the regeneration plant capacity of 10 tons per day, the available cash flow of 2.86 million USD per year, and discount rate of 7.5% per year. The calculated maximum profit ($\pi^{\max}$) for sole generation, sole regeneration and integrated cases were 0.103, 1.592, and 1.385 million USD per year, respectively. It was pronounced that the maximum annual profit obtained from the sole regeneration case was about 1.2- and 15.4-fold higher than that obtained from corresponding integrated and sole generation plants. Additionally, Table 2 shows the results of variables estimated from the optimization model.

For 10-year investment life of each case the initial capital investment of sole generation and sole regeneration plants were 4,689,566 USD, while that of integrated plants was 7,729,000 USD, see Table 1.

Table 2 shows increasing of the demand of AC (D) from the period of February-May until the period of October-January. From February to May coconut shell availability was low, so the amount of usable AC generated (Z_4) and that of regenerable spent AC (Z_1) were lowest for each case. Z_4 obtained from sole generation case was about 3.8-fold higher than that obtained from the integrated plants, while values of Z_1 obtained from both the sole regeneration and integrated plants were identical. During this period, the warehouse was completely empty to satisfy the total demand resulting in the highest profit since the inventory cost of 5.71 USD/ton was the lowest cost comparing to other costs. The purchase amount of virgin AC (Z_2) of sole regeneration case was lower than that obtained from sole generation case by a factor of 2 whereas there was no purchasing requirement of virgin AC for the integrated plants.

Not only had higher availability level of coconut shell during harvest period, June and September, but also the demand of AC was increased. It was found that Z_4 for the sole generation and integrated plants were identical while the AC amount taken from inventory (Z_3) for generation alone was 4.5-fold lower than integrated plants. Similar to February-May period, Z_1 obtained from the sole regeneration and the integrated plants were identical, while Z_3 for regeneration alone was 1.06-fold higher than that of integrated plants. As a result, Z_1 of this period for the sole regeneration and integrated plants was about 1.6-fold higher than that of period of February-May. To satisfy the total demand during this period the purchase amount of virgin AC (Z_2) for the sole regeneration plant was about 1.9-fold higher than the integrated plants.

During October to January there were more abundant amount of coconut shells plants were about 2-fold higher than that of period June-September. Similar to previous periods, optimal values of Z_1 obtained from both the sole regeneration and the integrated plants were identical due to the same set of input value of spent AC amount for both cases as shown in nomenclature. The remaining Z_3 from the previous period of regeneration alone was the lowest, causing the highest purchase amount of virgin AC (Z_2). To satisfy the total demand during this period the purchase amount of virgin AC (Z_2) of the sole regeneration plant was about 1.5-, and 2.2-fold higher than that of corresponding the sole generation and integrated plants.

The generation cost of AC (C_G) that was calculated only for sole generation and integrated plants was proportional to the usable generated AC amount (Z_4). The regeneration costs of spent AC (C_R) of both the sole regeneration and integrated plants were identical due to the same results of regenerated amount (Z_1). The C_R was proportional to Z_1 depending on the AC demand (D) of each time period.

The inventory of product (I) had a direct effect on the inventory cost (C_I). For example, during low AC demand period, February-May, the total initial inventory amount of AC was entirely taken resulting in small product amount required from generation and regeneration processes whereas during more plentiful coconut shell amount periods, June-September and October-January, the amount of AC generated was increased due to higher AC demand causing higher generation cost.

The purchase cost of virgin AC (C_P) was proportional to the purchase amount of virgin AC (Z_2). Evidently, the purchase cost of virgin AC obtained from generation alone was substantially higher than that obtained from sole regeneration and integrated plants since the purchase quantity of virgin AC in the sole regeneration and integrated plants could compensate by regenerating spent AC. Moreover, the outsourcing sales price of virgin AC offered by an external third party was about 1.2-fold higher than that of the sales price of AC produced causing the lowest profit for the sole generation plant. Thus, the maximum annual profit of the in-house generation plant at the optimal AC demand is shown in Fig. 2. The annual profit of the sole generation plant was increased from 103,107 USD to 689,170 USD when the AC demand for each period was given as [990 1,925, 2,310] ton/period or about 45% lower than the base case due to no requirement of procurement outsourcing of virgin AC.

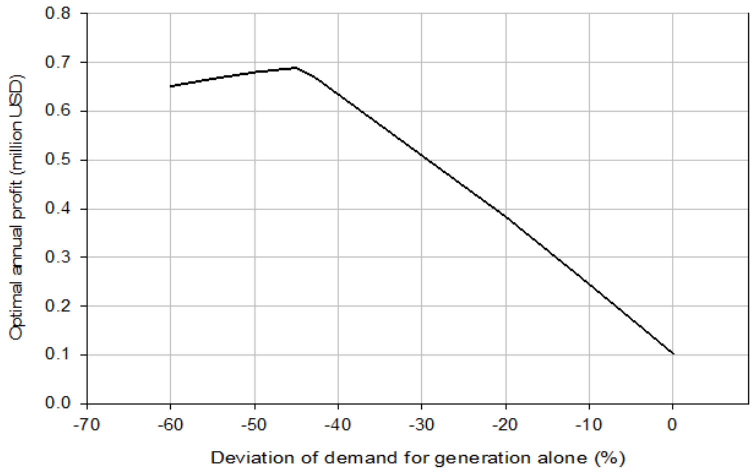

Fig. 2. Optimal annual profit at various deviation of AC demand for the sole generation plant.

4.2. Sensitivity analysis

To investigate the effect of possible changes in the calculated variables contributing to the cash flow on the project economic viability, a sensitivity analysis on main factors affecting the net present value (NPV) was studied. The six selected factors were fixed costs of generation (f_G) and regeneration (f_R), variable costs of generation (v_G) and regeneration (v_R), selling price (p) and purchasing rate (r) [5, 6]. Figure 3 shows the effect of variations of these six factors on NPV over the range -15 to +15%, with the 5% increment each time. Amongst these six parameters p was the most sensitive since small variation of p indicated the positive effect on NPV. Other parameters such as f_G, f_R, v_G, v_R

and *r* adversely affected to NPV. The least sensitive parameters to NPV were f_G, f_R and v_R. The increase in *p* gave the positive profit which was consistent with the study of Vanreppelen et al. [9]. In addition, lower values of v_G and *r* gave benefits to NPV.

The study of Stavropoulos and Zabaniotou [10] reported that project economic feasibility was influenced by selling price of product depending on its adsorption capacity, raw material cost and plant capacity. Similarly, amongst six selected factors such as variable cost of regeneration, selling price and purchasing rate, the selling price of AC was the most sensitive while the variable cost of regeneration was the least sensitive to the NPV [11].

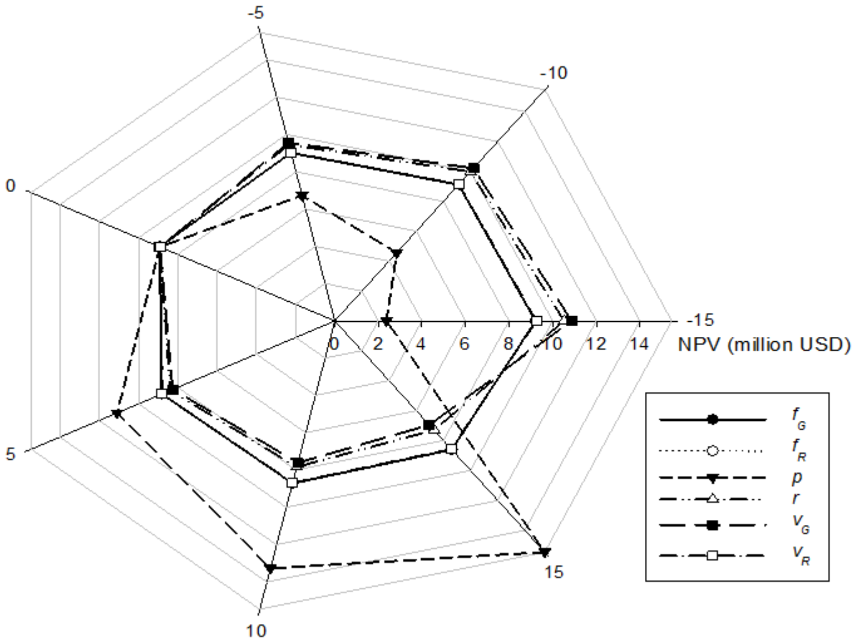

Fig. 3. NPV Sensitivity analysis of generation and regeneration cases.

4.3. Economic evaluation among three different processes

As shown in the result of sensitivity analysis, the sales price of AC was the most significant factor affecting the NPV of the project. Moreover, annual sales price of AC generated and regenerated were main revenues for all studied cases. The sales price, the most important indicator for the project growth, tends to be driven by continuing competition among suppliers, demand of AC and quality of AC [14]. Based on the maximum annual profit calculated from the optimization model, the estimation of economic indicators responsible for the project feasibility is shown in Table 3.

At low AC sales price, ROI of generation and integrated cases were negative representing greater annual cost than annual revenue (Fig. 4). When the sales price of AC was increased from 514 to 686 USD/ton of AC, ROI of generation, regeneration, and integrated plants were achieved 2.20, 33.94, and 11.02%, respectively.

Table 3. Formula and data of economic indices.

Return on investment (ROI):
It measures annual rate of return on capital investment. $\text{ROI} = \frac{\pi_t}{K} \cdot 100\%$ where K = total investment cost as shown in nomenclature and π_t = annual profit, see Table 2
Net present value (NPV):
It is the total income from the investment during its life span of investment. $\text{NPV} = \sum_{n=1}^{T} \frac{\pi_t}{(1+\delta)^n} - K$ where T = investment life of 10 years
Internal rate of return (IRR):
It is the interest rate that pays off the loan of entire investment. It is calculated by putting NPV(T=10 year) = 0. $\sum_{n=1}^{T} \frac{\pi_t}{(1+\delta^*)^n} - K = 0$ where δ^* = internal rate of return, IRR (%)
Simple payback period (SPP):
It calculates the time required for the pay-back of investment. $\text{SPP} = K / \pi_t$

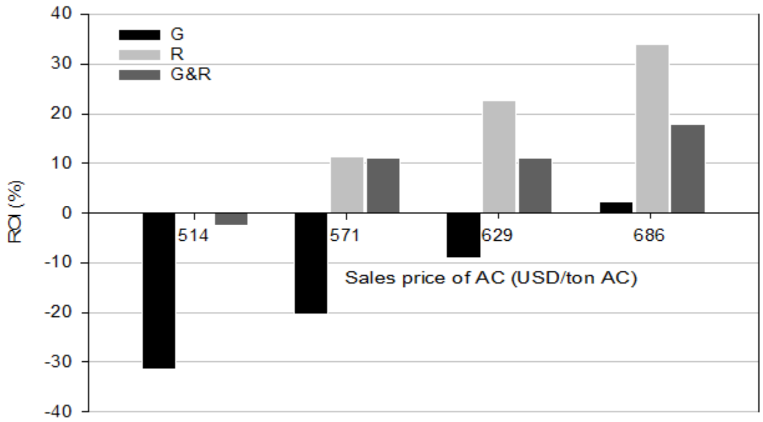

Fig. 4. Comparison of ROI as a function of AC sales price.

Similarly, the NPV for 10-year investment life obtained from all projects were proportional to AC sales price as shown in Fig. 5. Evidently, all positive NPVs of the regeneration case suggested the most profitability of the project for the entire studied sales price range.

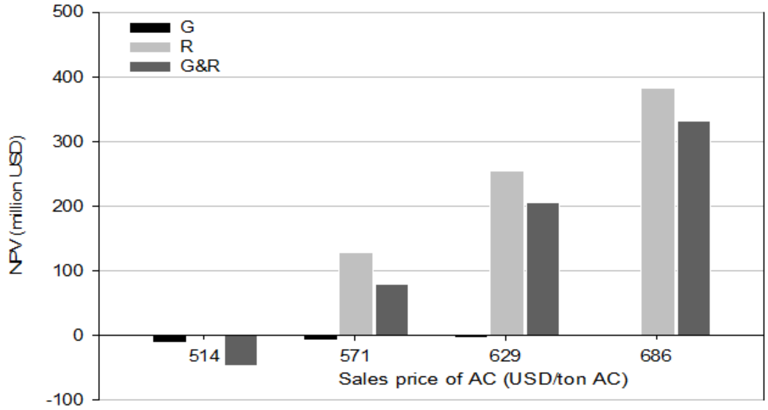

Fig. 5. Comparison of NPV for 10-year investment life as a function of AC sales price.

At the unchanged demand of product (*D*), availability of coconut shells (X_t) and spent AC (*Y*) and plant capacity, the variation of AC sales price affecting project economic indices such as SPP and IRR was investigated. SPP is the time duration when the profit derived from sale revenue equals to the total investment regardless of the discount rate. The study of Vanreppelen et al. [9] reported that the range of calculated payback period of AC production was 7 and 11 years. Thus, AC sales price was calculated when SPP was varied from 3 to 7 years, see Table 4. At the increase of SPP, the AC sales prices for sole generation, sole regeneration, and integrated cases were increased 0.30%, 0.39%, and 0.37%, respectively. The increment of SPP has more effect on sales price of product for sole regeneration than others due to its lowest fixed cost.

Table 4. Comparison of SPP for different AC sales price.

Plant scheme	Sales price (USD/ton AC)		
	SPP = 3 years	SPP = 5 years	SPP = 7 years
Generation	672.31	673.71	674.31
Regeneration	512.66	514.06	514.66
Integrated plants	534.69	536.07	536.66

A positive IRR means that the total revenue is greater than the total investment by considering time value of money. Table 5 shows the relationship between sales price and IRR given that the SPP is 7 years. When the IRR was increased from 10% to 18% per annum based on the assumption of unlimited raw material supply for both generation and regeneration processes, AC sales price for generation, regeneration, and integrated cases was increased from 319.23 to 319.76, from 285.52 to 286.04, and from 584.36 to 585.77 USD/ton AC, respectively. At the same IRR, it was pronounced that the AC sales price of integrated plants was the highest and that of the regeneration was the lowest due to predominant direct effect of fixed costs and adverse effect of v_G on IRR. To increase competitiveness of the AC, the minimum acceptable product sales prices based on a rule of thumb of discount rate of 12% per annum and 7-year simple payback period for generation, regeneration, and integrated plants were 674.31, 514.66 and 536.66 USD/ton of product, respectively. It is possible that AC sales price is higher in the future depending on the market demand [15].

Table 5. Comparison of IRR for different AC sales price when SPP is 7 years.

Plant scheme	**Sales price (USD/ton AC)**			
	IRR = 10% per annum	**IRR = 12% per annum**	**IRR = 15% per annum**	**IRR = 18% per annum**
Generation	319.23	319.35	319.55	319.76
Regeneration	285.52	285.64	285.84	286.04
Integrated plants	584.36	584.70	585.23	585.77

5. Conclusions

Sales price, the most sensitive parameter to NPV, directly affected ROI, SPP and IRR due to the predominant direct effect of fixed costs and adverse effect of variable cost of AC generation. The annual profit of the in-house generation plant could be improved by a factor of 6.7 when the AC demand for each period was 45% lower by avoiding procurement outsourcing of virgin AC. Amongst the three project plants, the economic feasibility of the sole regeneration plant of spent AC was the most profitable.

Acknowledgments

This work was supported by the Faculty of Engineering, Thammasat University. The author would like to thank Mr. Sangchai Theerakulwanich for the data collection.

References

1. Yehaskel, A. (1978). *Activated carbon manufacturer and regeneration*. Noyes Data Corp, New Jersey.
2. Ng, C.; Marshall W.E.; Rao M.R.; Bansode, R.R.; and Losso, J.N. (2003). Activated carbon from pecan shell: process description and economic analysis. *Industrial Crops and Products*, 17, 209-217.
3. Xin-hui, D.; Srinivasakannan, C.; and Jin-sheng, L. (2014). Process optimization of thermal regeneration of spent coal based activated carbon using steam and application to methylene blue dye adsorption. *Journal of Taiwan Institute of Chemical Engineering*, 45, 1618-1627.
4. Demirbas, A. (2011). Waste management, waste resource facilities and waste conversion processes. *Energy Conversion Management*, 52, 1280-1287.
5. Sufnarski, M.D. (1999). *The regeneration of granular activated carbon using hydrothermal technology*. M.Sc Thesis. University of Texas at Austin, Texas.
6. Knopp, P.; Meidl, J.; and Berndt, C. (1978). *Carbon adsorption handbook.* Ann Arbor Science, Michigan.

7. Mundale, V.D.; Kalam, A.; Joglekar, H.S.; and Joshi, J.B. (1991). Regeneration of spent activated carbon by wet air oxidation, *The Canadian Journal of Chemical Engineering*, 69(5), 1149-1159.
8. Modell, M.; DeFillipi, R.; and Krukonis, V. (1990). *Activated carbon adsorption of organics from the aqueous phase.* Ann Arbor Science, Michigan.
9. Vanreppelen, K.; Schreurs, S.; Kuppens, T.; Thewys, T.; Carleer, R.; and Yperman, J. (2013). Activated carbon by co-pyrolysis and steam activation from particle board and melamine formaldehyde resin: production, adsorption properties and techno economic evaluation. *Journal of Sustainable Development of Energy, Water and Environment Systems*, 1(1), 41-57.
10. Stavropoulos, G.G.; and Zabaniotou, A.A. (2009). Minimizing activated carbons production cost. *Fuel Process Technology*, 90, 952-957.
11. Skolpap, W.; and Theerakulwanich, S. (2013). Economic Feasibility of Regeneration Plant of Spent Activated Carbon. *KMITL Science and Technology Journal*, 13(2), 62-66.
12. Seyedi, I.; Mirzazadeh, S.; Malekidaronkolaei, A.; Mukhtar, M.; and Sahran, S. (2016). An inventory model with reworking and setup time to consider effect of inflation and time value of money. *Journal of Engineering Science and Technology*, 11(3), 416-430.
13. GAMS. (2016). Solver Descriptions. Retrieved December 27, 2016, from http://www.gams.com /solvers/solvers.html.
14. Cheung, C.W.; Choy, K.K.H.; Porter, J.F.; and McKay, G. (2005). Empirical multicom-ponent equilibrium and film-pore model for the sorption of copper, cadmium and zinc onto bone char. *Adsorption-journal of the International Adsorption Society*, 11(1), 15-29.
15. Ko, D.C.K.; Mui, E.L.K.; Lau, K.S.T.; and Mckay, G. (2004). Production of activated carbons from waste tire - Process design and economical analysis. *Waste Management*, 24, 875-888.