Article

Optimal Economic–Environmental Design of Heat Exchanger Network in Naphtha Cracking Center Considering Fuel Type and CO_2 Emissions

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Abstract: In the petroleum industry, naphtha cracking centers (NCC), which produce ethylene, propylene, propane, and mixed-C4, are known to consume a large amount of energy and release a significant amount of carbon dioxide (CO_2). This necessitates economic and environmental assessments with the aim of achieving a reduction in energy use in order to ensure efficiency in terms of cost and environmental impact. Herein, a heat exchanger network (HEN) is considered with the aim of determining its optimal operating strategy. In addition, the trade-off between reduction in utility costs (i.e., profit) and the installation cost of the heat exchanger (i.e., loss) is evaluated in terms of economic efficiency. Finally, an environmental impact assessment is performed with respect to the source of fuel consumed for steam generation. The HEN's energy consumption in the three configurations analyzed herein was found to be reduced by 3%, 6%, and 8%. When considering variations in the fuel used for steam generation, the changes in the payback period caused differences in the results for the most economical configuration. On the basis of this study, it was possible to design the use of waste heat in the pinch network and the network configuration for the installation of additional heat exchangers in an economically feasible manner, while analyses of various fuel source were used to determine favorable conditions with respect to environmental impact.

Keywords: naphtha cracking center; heat exchanger network; heat transfer enhancement; economic assessment; environmental assessment

1. Introduction

Ethylene, a significant material in the petrochemical industry, is the simplest hydrocarbon, and is used to synthesize various composite materials in the manufacturing industry. Ethylene production methods include naphtha cracking (NC), ethane cracking (EC), and coal to olefin (CTO) [1]. To produce ethylene, a naphtha cracking center (NCC) thermally cracks naphtha refined from crude petroleum, an ethane cracking center (ECC) uses ethane extracted from natural gas and shale gas, and a CTO facility produces chemicals from coal synthetic gas [1]. Among these options, NC has the advantage of providing a large range of downstream olefins (ethylene, propylene, etc.) and aromatics (benzene, toluene, xylene, etc.) [1]. However, the energy required for the NC process accounts for approximately 40% of the total amount of energy used in the petrochemical industry, because it is necessary for the thermal cracking reactors to be operated at high temperatures (>800 °C) [2,3]. Thus, to ensure sustainability, the energy consumption of this process must be reduced. In this regard, various technologies for energy-efficient NC have been investigated.

For example, NC can refer to several separation processes for materials production. Advanced separation technologies have been proposed and applied, because this process is considered to be the most expensive and energy-intensive process. Olefin–gas separation based on membrane technology has recently been proposed and investigated with the aim of overcoming the drawbacks of this technique. Daviln et al. [4] explained that olefins are currently separated via cryogenic distillation, which requires extremely high pressures

and low temperatures. The area in which energy consumption could be reduced is the cryogenic isolation of hydrocarbon production from the reaction byproducts. Olefin–gas separation concentrates on improving the capillary condensation process that separates olefinic composites. Motelica et al. [5] proposed butadiene separation, which can reduce energy consumption by 30% by means of the membrane and process arrangement. Lee et al. [6] developed propylene/propane gas separation membranes in place of a C3 splitter for naphtha cracking plants. Kumar et al. [7] described an adsorption–distillation hybrid formation that was able to reduce energy consumption by 50% and the capital costs related to modern technology by 15–30% for propane/propylene separation. The main point of the suggested design is to split olefins from alkanes via adsorption. Subsequently, the olefins fraction is separated into olefins and alkanes by means of an easy distillation method. Based on a detailed study of currently adopted strategies, Parmar et al. [8] showed that energy consumption decreased by 68% in the feed purification unit (FPU) after applying heat integration in both separation units, while heat use increased in the propylene (PE) fractionator column. In addition, propylene losses were found to be minimized. A significant operational improvement was reported by enhancing safety, which was accomplished without major revision and cost for industrial operation, with a reduction in energy consumption reaching 70% and product recovery reaching 3%. Dimian et al. [9] designed a methanol-to-olefin (MTO) process in order to develop an adequate energy and cost system. This innovative solution consisted of fully recovering the energy generated by the reaction. The effluent enthalpy of the reactor made the remaining energy available for the processes of preheating, evaporation, and superheating. This method, which uses vapor compression, was developed by recovering the energy from water quenching. The energy saved meant that the point at which the cost of the compressor was compensated for was achieved within one year. The energy derived from the reactor is used to operate a power cycle with integrated heat. Tahouni et al. [10] reconstructed an olefin plant in order to upgrade its energy efficiency. The effects of upgrading the column operation parameters and refrigeration cycle parameters were evaluated first. Subsequently, the column operation parameters, refrigeration cycle parameters, and HEN were optimized using the genetic algorithm or simulated annealing. In Christopher et al. [11], mechanical vapor recompression (MVR) and self-heat recuperation (SHR) were evaluated in combination for application in cases involving distillation. The best results were obtained when MVR and SHR were used at the same time. MVR removes the necessary steam for the reboiler, while SHR uses the remaining sensible heat to heat up streams in order to feed the compressor, and which are then fed forward for MVR, resulting in a decrease in energy consumption of 45% and a 20% decrease in separation costs, when compared to the MVR design without SHR. Dimian et al. [12] presented a design for a sustainable process for manufacturing acetic acid, which is a crucial product in the chemical industry, through methanol carbonylation utilizing a heterogeneous catalyst. The most important aspect of this technique was the valorization of the energy from the exothermic reaction. Energy efficiency was improved via steam generation and vapor compression combined with an organic Rankine cycle. A catalytic reaction is essential in order to reduce the chemical reaction temperature. Using a catalyst in the cracking process can reduce the NC operating temperature to 573–700 °C. Khoshbin et al. [13] proposed a hierarchically structured ZSM-5 running at an operating temperature of 523–700 °C using a sonochemical-assisted carbon nanotube in order to analyze the catalytic activity in cracking naphtha. The catalyst activity differed depending on the CNT carbon nanotubes (5, 15, and 30 wt%). As a result, the total energy consumption was diminished by 10–20%. Pinch analysis has been considered and adopted as an efficient technique for energy utilization. However, according to Jahromi et al. [14], it suffers from limitations and defects with respect to application in heat exchanger retrofitting; therefore, they produced a diagram describing super-ambient, sub-ambient, and sub-ambient temperature processes. This design represented an attempt to improve the heat exchanger network's (HEN) methanol-to-propylene (MTP) efficiency and maximize economic profits.

HENs are essential for saving energy in the process industry. They facilitate heat integration using heat exchangers and hot/cold process streams to decrease utility consumption. Aas [15] reported that HEN synthesis includes the total number of units (U), energy consumption (E), and heat transfer area (A). Liu et al. [16] showed that HENs in the syngas-to-methanol process can be constructed using pinch analysis to optimize the balance between energy consumption and economical benefit. A flexible HEN was developed using the synthesizing streams, leading to a 13.90% decrease in energy consumption and a 20.82% decrease in total cost, with these factors being minimized using the downstream path method. Paiko et al. [17] discussed the optimization of a HEN in order to reduce energy consumption in a naphtha hydrotreatment unit (NHU). The HEN for the NHU plant was constructed using Aspen Pinch and complied with the pinch analysis. Beninca et al. [18] presented a pinch analysis in order to analyze the thermal integration opportunities in existing olefin plants, and to quantify and identify reductions in energy consumption by altering the existing HENs to achieve these goals. Zhao et al. [19] pointed out that the use of waste heat from the production of methanol and ammonia can reduce energy consumption and CO_2 emissions. A HEN was designed using pinch analysis with the aim of reducing utility.

The NC process has multiple operating disadvantages; therefore, it is necessary to develop methods to reduce its energy consumption. Therefore, in this study, an HEN was reconstructed using waste energy, and an economic evaluation was performed in consideration of the changes in heat exchanger cost and utility savings arising from changes in the number of heat exchangers. Furthermore, from an environmental point of view, environmental damage costs can be regarded as revenue when the use of CO_2 is reduced owing to emission factors. To diminish the energy consumption of the NC process, we designed an optimal HEN through economic valuation using the payback period and the environmental impact based on environmental damage costs.

2. Methodology

2.1. Process Description

The HEN, in which the waste energy from the hot and cold streams is used for the construction of heat exchangers instead of using utilities (steam, cooling water, etc.), is one method of increasing the efficiency of energy consumption in the NC process. Essentially, heat exchangers are used to transport heat energy. Heat exchange occurs because of the complementary effect of energy exchange between a hot stream that has to be cooled down and a cold stream that has to be heated up. With increasing use of waste energy, utility savings increase, but the cost of the heat exchangers also increases. Therefore, the utility savings are considered revenue, while the heat exchanger cost represents the loss. The revenue from utility reduction stands in a trade-off relationship with the cost of the heat exchangers when the assessment model referred to as the payback period is used [20] (Figure 1).
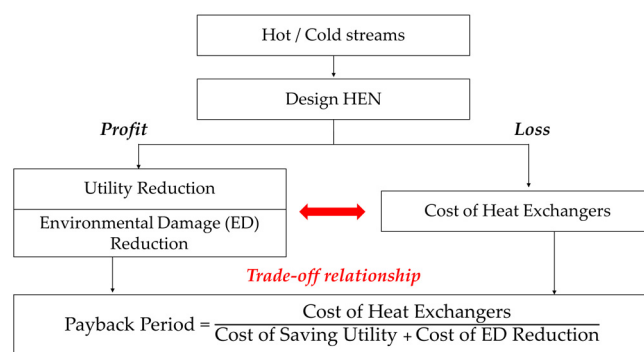

Figure 1. Simplified diagram of economic–environmental impact assessment strategy.

An economic assessment considering the trade-off and trends between the revenue from utility reduction and the loss owing to the cost of heat exchangers with changing numbers of heat exchangers was performed. Therefore, multiple design configurations are constructed by adding heat exchangers one by one, and the fluctuation in the payback period for each configuration is assessed. Additionally, with regard to environmental considerations, reduced environmental damage can be considered to be revenue when there is a decrease in the use of utilities that emit CO_2 in the production of superheated steam. The type of fuel used to generate steam can vary, affecting the amount of CO_2 emissions and the cost of steam, contributing to fluctuations in the payback period.

2.2. Naphtha Cracking Center (NCC)

NC is implemented in four steps: (1) pyrolysis, (2) quenching, (3) compression, and (4) fractionation. Its flow diagram is shown in Figure 2.
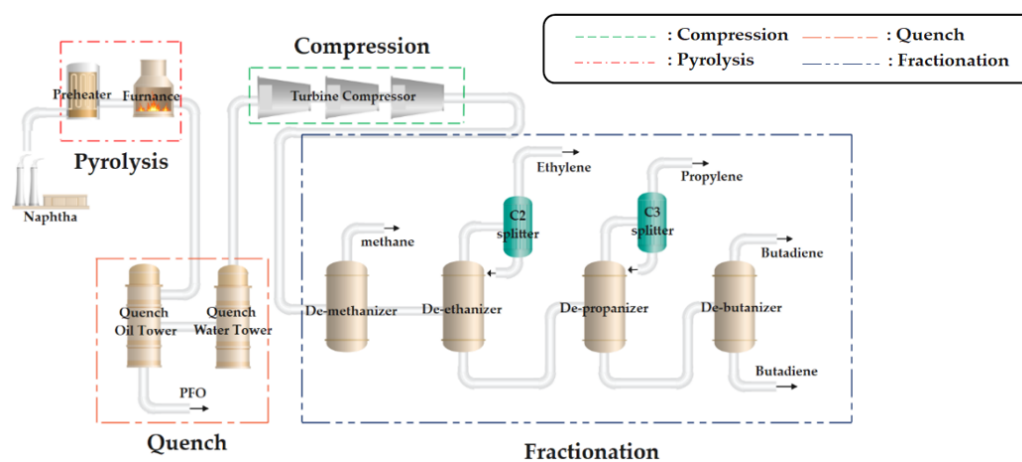
Figure 2. Process flow diagram of NC.

(1) Pyrolysis. In pyrolysis, naphtha is cracked into smaller molecules, such as light olefins and aromatics, which requires a large amount of thermal energy, as it is an endothermic reaction. First, naphtha, preheated by the convection section to 650 °C, enters the furnace of the pyrolysis section and is heated to 750–900 °C using fuel oil or gas; subsequently, naphtha is cracked within the space of a fraction of a second (0.4–1 s) [21]. Next, the cracked gas must be cooled to stop any side reactions.

(2) Quenching. This can be divided into two types of direct cooling system—systems that use quenching oil and systems that use quenching water—that cool the cracked gas from 800–900 °C to 300–425 °C. The cracked gas consists of hydrocarbon gases, which can easily transform aromatics and polyaromatics. Therefore, the quenching section provides a cooling system to prevent the formation of coke, tar, and polyaromatics by polymerization and to maintain a low carbon number. After the cooled gas is supplied to the gasoline fractionator, it produces pyrolysis fuel oil (PFO) [22] at the bottom of the tower. The gas is processed at the top of the tower. The processed gas is then transported to undergo the compression process.

(3) Compression. The processed gas from the quenching tower is compressed in order to achieve economical fractionation. The compression section has centrifugal compressors in 4–6 stages, which increase the pressure of the processed gas from 1–2 bar to 40–50 bar [23]. To clean the compressed gas, a cleaning tower between the 3rd and 4th stage of compression removes the toxic substances H_2S and CO_2 for fractionation.

(4) Fractionation. The compressed gas is separated into H_2, methane, ethylene, propylene, and mixed C-4 using the low-temperature fractionation method. The compressed gas enters the de-methanizer and the methane is separated out at the top of the column. When the gas from the bottom of the de-methanizer is forwarded to the de-ethanizer, the

C_2 components are split at the top of the column. The gas at the bottom of the de-ethanizer, including the C_{3+} components, is separated from the C_{4+} components at the top of the de-propanizer. The C_{3+} components, passing through a propylene fractionated C_{4+} component, are sent to the de-butanizer in order to manufacture C_4s and pyrolysis gasoline [23].

2.3. Energy Reduction Technique

HENs are an effective way of reducing energy consumption in chemical processes such as NC, because there is no need to change the structure of the process when HENs are used; instead, the system is retrofitted with heat exchanger arrangements [18]. The design of a HEN is based on the pinch analysis proposed by Linnhoff et al. [24,25], which is used to calculate the minimum utility requirement with respect to the minimized number of units and the minimized surface area [24]. The composite curve (Figure 3), drawn with hot and cold steam data, displays the required energy and the pinch point, which are essential for the design of HENs.
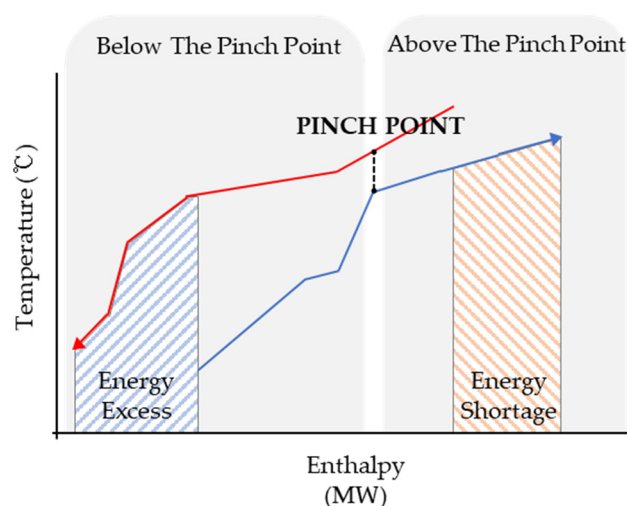
Figure 3. The composite curve drawn with hot and cold streams.

There are two thermodynamic regions of the composite curve: one of these is "above the pinch point", and is characterized by energy shortage, requiring only the hot utility; the other is "below the pinch point", and has an excess of energy, requiring only the cold utility. Heat exchangers are added to cover this heat differential without the need for any utilities originating from outside the process. However, there are some restrictions when performing pinch analysis: (1) heat exchangers are not able to cross the pinch point; (2) the temperature of the hot utility should be lower than the pinch-point gap; and (3) the components of the hot utility should be steam [26,27]. The reason for the first restriction is that if a heat exchanger crosses the pinch point, the energy consumption will be higher than the minimum requirement. The second restriction is that heat exchange does not occur if the temperature gap between the hot and cold streams is greater than the pinch-point gap. The third restriction, whereby the utility that is to be replaced is steam, is necessary because it is more expensive than other utilities and can be discarded more easily than other streams, which can be used as utilities in the process.

2.4. Economic–Environmental Impact Assessment

An economic–environmental impact assessment was conducted to evaluate the reduction in utility usage and the impact of CO_2 on the configurations. As mentioned earlier, the principle of the payback period was adopted. The payback period is an indicator of the value criterion in economic assessment. Payback time refers to the time it takes to recover

all investments, and is expressed in months. The following equation is used to determine the *payback period* [28]:

$$Payback\ period(monthly) = \frac{P}{ACI} \tag{1}$$

where P is the project cost in USD and ACI is annual cash inflows in USD/yr. P is calculated as [29]

$$P = C_{hx} = A \times \left(B + C \times Area^D\right) \tag{2}$$

where C_{hx} is the cost of the heat exchanger in USD, $Area^D$ is the heat exchange area in m^2, A is 3, B is 33,422, C is 814, and D is 0.81 [29].

Annual cash inflow (ACI) is calculated in two ways: Equation (3) includes only the benefit of saved steam cost, and does not include the environmental impact:

$$ACI = C_{SSC} = C_{ST} \times \dot{m}_{RS} \tag{3}$$

where C_{SSC} is the cost of the reduced steam flow rate in USD/yr, C_{ST} is the cost of steam in USD/ton steam, and $\dot{m}_{RS}$ is the reduced steam flow rate in ton/h.

$$ACI = C_{SSC} + C_{ED} \tag{4}$$

Equation (4) includes the benefit of the saved steam cost and the reduced environmental damage, which includes the environmental impact. C_{ED} is the cost of the reduction in environmental damage in USD/yr, derived on the basis of the reduced flow rate of steam and the CO_2 emission factor.

$$C_{ED} = \dot{m}_{RS} \times F_{CO_2} \times E_{MP,LP} \times C_{EM} \tag{5}$$

where F_{CO2} is the emission factor of CO_2 in Table 1, C_{EM} is the cost of CO_2 emission, which is 0.024 USD/kg [30], and $E_{MP,LP}$ represents the energy required to generate middle-pressure (MP) or low-pressure (LP) steam [31].

Table 1. Data for the emission factor of CO_2 (F_{CO2}).

Energy Source	F_{CO2} (kg CO_2/MWh) [32]
Coke	385.2
Peat	381.6
Lignite	363.6
Anthracite	353.88
Sub-bituminous	345.96
Bitumen	290.52
Charcoal	403.2
Municipal wastes	330.12
Waste plastic	214.91 [33,34]
Natural gas	201.96
Biogas	196.56
Solar	0

In order to conduct an environmental assessment, it is necessary to make an assumption regarding steam price derived from different fuel types, because the steam cost changes with their different heating values, and the price contributes to the results of the economic assessment. The assumption of steam price is expressed as follows [35]:

$$C_{ST} = C_{var} + C_{fix} \tag{6}$$

where C_{var} represents the variable costs that are affected by manufacturing rate, feed cost, etc., in the industry's status, and C_{fix} represents the annualized fixed costs, including capital costs and labor costs, on which spending occurs regularly.

$$C_{var} = C_F \times F_{BF} + C_{RW} + C_{CH} + C_{PW} \tag{7}$$

where C_F is the fuel cost, F_{BF} is the average boiler fuel, C_{RW} is the fresh raw water supply cost, C_{CH} is the water chemical treatment cost, and C_{PW} is the cost of power required for water pumping and boiler air fans.

$$C_{fix} = \frac{R \times C_{Inv} + C_M + C_O}{\sum m} \tag{8}$$

C_{Inv} is the capital investment, R is the fraction of C_{Inv} depreciated annually, C_M is the material and labor cost, C_O is other costs, and $\sum m$ is the total steam generation from the boiler [35]. The data for the assumption of steam prices are presented in Table 2 [35].

Table 2. Data for the assumption of C_{var} and C_{fix}.

C_{var}		C_{fix}	
F_{BF}, average boiler fuel [MMBtu/1000 Ib steam]	1.56	C_{Inv}, boiler capital cost [MMUSD]	20
C_{RW}, freshwater [USD/1000 Ib steam]	0.02	R [% of capital cost]	15
C_{CH}, water treatment cost [USD/1000 Ib steam]	0.74	C_M, material and labor cost [USD/yr]	360,000
C_{PW}, power requirement for water pumping, and boiler air fans cost [USD/1000 Ib steam]	1.77		

C_F (fuel) appears in USD/MMBtu, but most fuel costs are set up in USD/kg. Therefore, assuming a fuel cost in USD/MMBtu, we use Equation (9).

$$C_F = HV \times C_S \tag{9}$$

where HV is the heating value of fuels and C_S is the cost of the source, as shown in Table 3.

**Table 3.** Parameters for estimating the steam cost.

Energy Source	HV (kcal/kg Source)	C_S (USD/kg Source)	C_F (USD/MMBtu)	$C_{ST, MP}$ (USD/ton)	$C_{ST, LP}$ (USD/ton)
Coke	-	-	3.6 [36]	18.95	18.62
Peat	-	-	4.6 [37]	21.93	21.55
Lignite	-	-	0.00283 [38]	8.148	8.008
Anthracite	4519 [39]	0.14 [40]	7.812	31.59	31.05
Sub-bituminous	5013 [41]	0.186 [42]	9.205	35.77	35.15
Bitumen	6810 [43]	0.2 [44]	7.406	30.37	29.84
Charcoal	5982 [20]	0.15 [45]	6.324	27.12	26.65
Municipal wastes	4612 [46]	0.03453 [47]	1.888	13.80	13.56
Waste plastic	10,473 [33]	0.19 [48]	4.575	16.94	16.65
Natural gas	-	-	-	17.57 [49]	16.81 [49]
Biogas	-	-	-	27.89 [49]	27.42 [49]
Solar	-	-	-	33.22 [49]	32.50 [49]

The cost of reduced environmental damage (C_{ED}) and the steam cost (C_{ST}) are indicators that affect the fluctuation of the payback period, because F_{CO2} and C_{ST} change when considering the environmental impact.

3. Results and Discussion

3.1. Case Study

This study used data extracted from an actual NCC in South Korea. Tables S2 and S3 in the Electronic Supplementary Information (ESI) show the operating parameters of the hot and cold streams in the NCC used to construct a composite curve. After determining the hot and cold streams, the pinch network of the NCC was designed using Aspen Energy Analyzer (Aspentech) using ΔT_{min} of 20 °C. The composite curve shows that the pinch point is 187–167 °C, the required heating duty is 12.90 MW, and the cooling duty is 41.99 MW. The waste energy is determined in order to construct a HEN that is able to recover the required heating and cooling duty. Based on the information from the site, the H8 and H7 streams, whose inlet temperatures are both 160 °C, can reach outlet temperatures of 130 °C and 155 °C, respectively. Under these circumstances, configurations able to improve economic efficiency by adding heat exchangers were constructed using hot streams H8 and H7. Furthermore, applicable utilities consisting of steam and which have a lower temperature gap than the pinch point gap need to be chosen according to the restrictions of the pinch analysis, as listed in Table S1 in the ESI. Based on this information, the base case of HEN is shown in Figure 4a (the original version is shown in Figure S1 in the ESI).
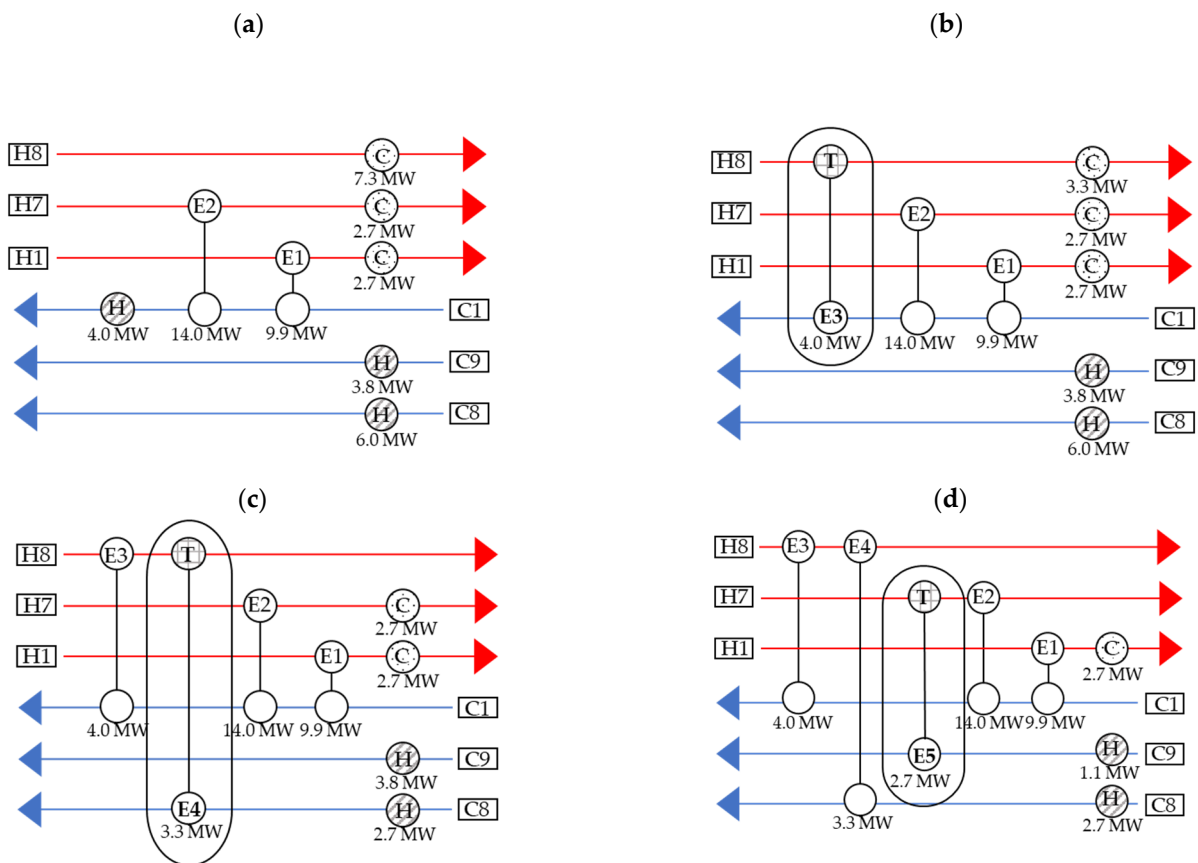
Figure 4. (**a**) Base case, (**b**) Configuration 1, (**c**) Configuration 2, (**d**) Configuration 3 (C: Cooler, H: Heater, E: Heat Exchanger).

For Configurations 1, 2, and 3, as shown in Figure 4, by adding heat exchangers one by one, the steam flow rate supplied by the heat utility decreases.

In Configuration 1, the C1 stream needs to be heated from 10 °C to 121 °C. C1 is connected to two exchangers. Subsequently, the amount of energy required by C1 is 4.0 MW. A heat exchanger connects C1 and H8, where 4.0 MW of heating and cooling duty is covered. H8 still has waste heat energy; therefore, a heat exchanger is attached to H8 in Configuration 2. In Configuration 2, the C8 stream needs to be heated up from 79.4 °C to 83.8 °C. A heat exchanger connects C8 and H8, and 3.3 MW of heating and cooling duty is covered. In Configuration 3, the C9 stream needs to be heated from 82.7 °C to 88.0 °C. A heat exchanger connects C9 and H7, and 2.7 MW of heating and cooling duty is covered. The results of the HEN are shown in Figure 5.
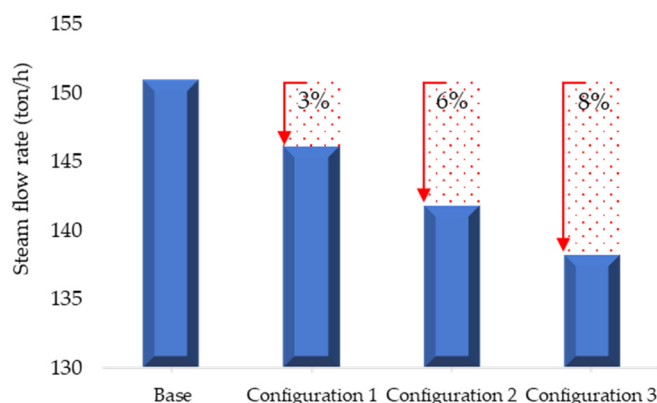

Figure 5. Decrease in the steam flow rate for Configurations 1, 2, and 3 compared to the base case.

Heat exchangers can be added to maximize the decrease in the steam requirement. The total steam flow rate is reduced by including a heat exchanger. The steam flow rates of the base case and Configurations 1, 2, and 3 were 150.9, 146.097, 141.823, and 138 ton/h, respectively. The energy analysis provides the maximum decrease in steam requirement, which is 8%. Still, we should assume an economic benefit as a result of the costs saved regarding steam loss as a result of installing heat exchangers.

3.2. Economic–Environmental Design

Because heat waste is generated in the quenching sector, energy consumption in the quenching sector must be reduced. In addition, the steam fuel used in the case study is natural gas, which is usually used to generate steam. The reductions in steam flow rate for Configurations 1, 2, and 3 are 4.803 ton/h (MP steam), 9.077 ton/h (MP and LP steams), and 12.661 ton/h (MP and LP steams), respectively. The payback period, without considering the environmental impact, is shown in Figure 6 as a bar graph.
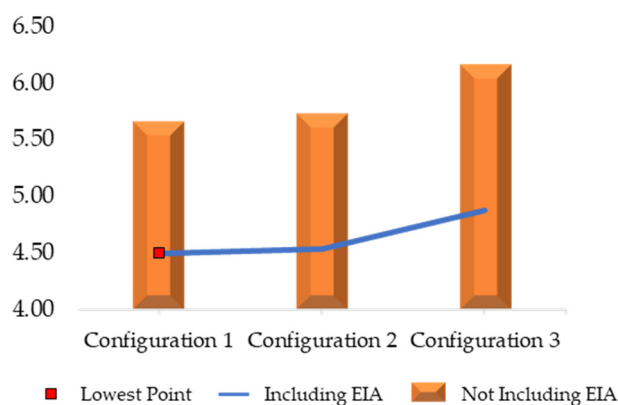

Figure 6. The payback period for natural gas.

The payback periods for Configurations 1, 2, and 3 are 5.66 months, 5.73 months, and 6.15 months, respectively. The lowest payback period was achieved with Configuration 1, which provided the fastest return on investment, at 5.66 months. Therefore, Configuration 1 is the most economical. From the point of view of the environment, producing steam by burning fossil fuels or multiple fuels in a boiler generates waste products during combustion, including SO_X, NO_X, and CO_2, which are harmful to the environment [50]. The revenue implied by carbon dioxide is considered to be equal to the reduction in environmental damage caused by reducing steam consumption to an extent equal to that of the decrease in CO_2 emissions. Therefore, when considering environmental impact, the configuration with the lowest payback period may change. The payback period taking into consideration environmental impact uses Equation (4), and the results are shown in Figure 6 as a line graph. The payback periods for Configurations 1, 2, and 3 are 4.49 months, 4.54 months, and 4.87 months, respectively. The lowest payback period is achieved with Configuration 1, which, at 4.49 months, provides the fastest return on investment. Therefore, Configuration 1 is still the most economical in terms of the economic assessment. However, when the payback period takes the steam source into consideration, this can change.

3.3. Economic–Environmental Design Considering Fuel Types

Currently, coal is being replaced by natural gas owing to the advantages of natural gas, such as lower CO_2 emissions. In Great Britain, switching fuel from coal to natural gas decreased annual emissions per-capita by 400 kg CO_2 [51]. However, coal is cheaper. Besides, renewable fuels such as biogas, biomass, and municipal wastes can be considered as fuels for steam. In particular, waste plastic gets attention due to its remarkable heating value. According to market value, we considered various fuels to generate steam and divided them into two categories: (1) petroleum energy and (2) renewable energy. Petroleum energy sources include coke, peat, lignite, anthracite, sub-bituminous, and bitumen, whereas renewable energy sources include charcoal, waste plastic, municipal waste, solar, and biogas. In addition, the result is focused on the comparing the payback period from fuel individually, not comparing the payback period between fuels.

The payback period can be changed by reducing the environmental damage using various fuel types. Each fuel has CO_2 emission factors and steam costs, as listed in Table 3. According to these data, the fluctuation of the payback period affected by the number of heat exchangers can appear differently. Fluctuations in the payback period with two representatives fuel categories are shown. The entire payback period is shown in Figures S2 and S3 of the ESI.

When the environmental impact is not included, the lowest point of 6 out of 6 petroleum fuels is for Configuration 1 (Figure 7); as the number of heat exchangers increases, the worse is the payback period.
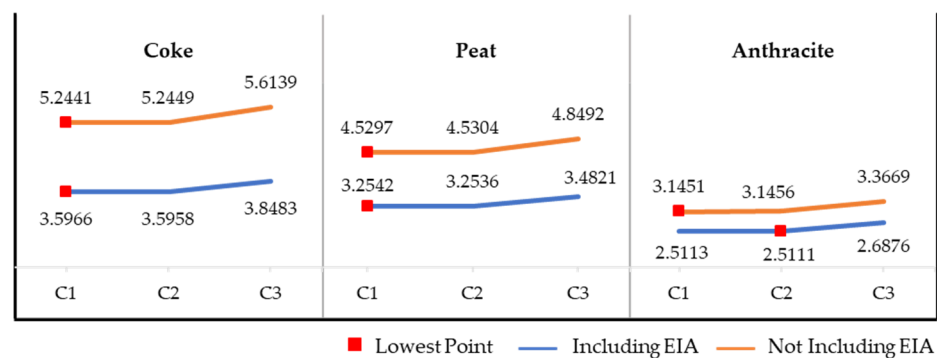

Figure 7. Payback period of petroleum fuels; C represents "configuration".

However, when the environmental impact is included, the lowest point of 6 out of 6 petroleum fuels is for Configuration 2. The payback period of petroleum fuels is significantly affected by the environmental impact equivalent to CO_2 emissions. In other

words, it influences fluctuations in the payback period of petroleum fuels, indicating a significant impact on CO_2 emissions. When fuels are renewable, fluctuations in the payback period are divided according to the CO_2 emission factor.

Renewable fuels, which have over 200 kg CO_2/ MWh of CO_2 emission factors assume an aspect that is the same as that of petroleum fuels. However, renewable fuels, which have below 200 kg CO_2/MWh of CO_2 emission factors did not show any fluctuation in the payback period whether including environmental impact or not (Figure 8). According to this, fuels to produce steam emit different CO_2 emissions and affect the economic–environmental assessment.
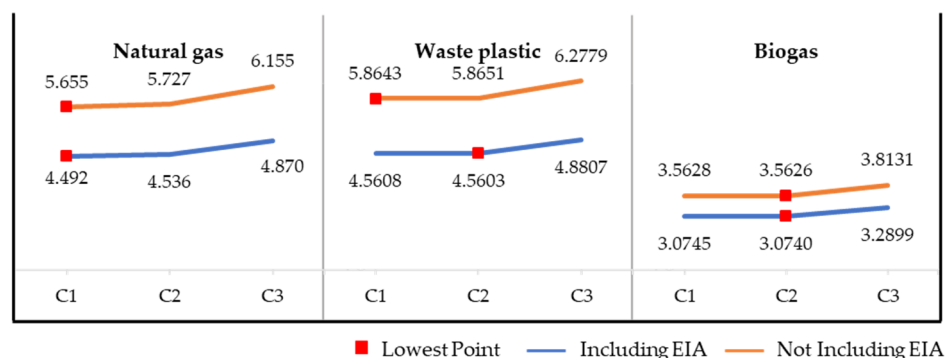

Figure 8. Payback period for renewable fuels; C stands for configuration.

In this study, NC, which is used to crack multiple monomers from naphtha, was considered as the main process in order to simultaneously assess the economic and environmental impacts, and the optimal operating conditions were determined by considering new HENs, which are essential factors in the design of an economically and environmentally benign process. it was found that several environmental parameters caused variations in the optimal design of the heat exchanger network. This study could be further extended in order to evaluate several environmental impacts, including CO_2 emissions, by considering the actual environmental parameters.

4. Conclusions

In this study, we used a novel approach to derive a strategy for determining the fluctuation in the NC process in terms of the payback period, when taking into consideration the number of heat exchangers when the steam source is changed. For the economic and environmental impact of fluctuations in the payback period, several NC configurations, Configurations 1, 2, and 3, were considered, whereby heat exchangers were added one by one. Variations in the CO_2 emission factor and the cost of steam, which are affected by steam sources, caused changes in the results for economic benefits. Based on these restrictions, the following results were obtained:

- The reduction in the steam flow rate is related to the economic assessment. The steam flow rate was calculated to be 150.9 ton/h for the base case. After constructing the HEN, the calculated steam flow rates were 146.097 ton/h for Configuration 1, 141.823 ton/h for Configuration 2, and 138.239 ton/h for Configuration 3. Therefore, 3%, 6%, and 8% reductions were found for Configurations 1, 2, and 3, respectively, compared to the base case.
- The cost of the heat exchanger and the saved cost due to the reduction in steam flow rate are essential for evaluating the economic–environmental impact. When natural gas was considered as the fuel, the amount of CO_2 reduction of Configuration 1, 2, and 3 was 8.0, 15.0 and 20.8 kilo ton(kton) CO_2/yr, and the amount of CO_2 reduction was calculated as revenue by multiplying it with the cost of CO_2 emission (C_{EM}). The payback period was used as an assessment method, with results of 5.66, 5.73 and 6.16 months without the EIA and 4.50, 4.54, and 4.88 months when including the EIA.

> These fluctuations, both when including the environmental impact and otherwise, were equal.
> - When taking changes in the fuel used for steam generation into consideration, the fluctuation in the payback period revealed the most economical configuration in terms of environmental impact.
>
> This study is expected to contribute to determining an economic and environmentally friendly assessment methodology for commercialized NC and other chemical processes.

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Nomenclature

$\dot{m}_{RS}$	Flow rate of reduced steam [ton/hour]
$\sum m$	Total steam generation from boiler [kIb/yr]
ACI	Annual cash inflows [USD/yr]
$Area$	Heat exchange area [m^2]
C_{CH}	Water chemical treatment cost [USD/kIb]
C_{ED}	Cost of reduced environmental damage [USD/yr]
C_{EM}	Cost of CO_2 emission [USD/kg]
C_F	Fuel cost [USD/MMBtu]
C_{fix}	Annualized fixed cost [USD/kIb]
C_{hx}	Cost of a heat exchanger [USD]
C_{Inv}	Capital investment [USD/yr]
C_M	Material and labor cost [USD/yr]
C_O	Other cost [USD/yr]
C_{PW}	Power requirement for water pumping and boiler air fans cost[USD/kIb]
C_{RW}	Fresh raw water supply cost [USD/kIb]
C_S	Cost of source [USD/kg]
C_{SSC}	Cost of the saved flow rate of steam [USD/yr]
C_{ST}	Steam cost [USD/ton]
CTO	Coal to olefin
C_{var}	Variable cost [USD/kIb]
E	Required energy [MWh/ton]
ECC	Ethane cracking center
F_{BF}	Average boiler fuel [MMBtu/kIb]
F_{CO2}	Emission factor of CO_2 [kg/MWh]

FPU	Feed purification unit
HEN	Heat exchange network
HV	Heating value [kcal/kg]
LP	Low-pressure steam
MP	Middle-pressure steam
MTO	Methanol to olefin
MTP	Methanol to propylene
MVR	Mechanical vapor recompression
NCC	Naphtha cracking center
NHU	Naphtha hydrotreating unit
P	Cost of the project [USD]
PE	Propylene fractionator
PFO	Pyrolysis fuel oil
R	Fraction of C_{Inv} depreciated annually [%]
SHR	Self-heat recuperation

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