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# Environmental sustainability enhancement of a petroleum refinery through heat exchanger network retrofitting and renewable energy

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**ABSTRACT**

This paper presents a case study on the enhancement of environmental sustainability in a petroleum refining process based on an exergetic diagnostic approach. The Life Cycle Assessment (LCA) pinpointed crude oil production and electricity generating systems as the main sources of environmental unsustainability. The existing hot utility demand of the process is 78.4 MW with a temperature difference of 40°C, where the area efficiency of the existing design is 0.7254. The targeting stage sets the minimum approach temperature at 18.96 °C, thereby establishing the scope for potential energy savings. The suggested design option with a total energy demand of 109,048 kW, the same as the existing one but 72,699 kW higher than the target, needs a 17,873 $m^2$ area in 38 exchangers. Notably, this requires 2,914 $m^2$ less surface area, suggesting the practicality of the project with a limited number of modifications such as the repiping of the existing exchanger units. Moreover, to enhance further the sustainability of the petroleum refining process, the possible solutions such as the renewables were evaluated through various scenarios; thus, resulting in a reduction in the environmental impacts from 2.34E-06 to 2.27E-06 according to ReCiPe, and thus paving the way towards a sustainable petroleum refining process.

## 1. Introduction

In spite of the importance of the petroleum refining process, there are few examples in the literature that use exergy analysis on a stand-alone basis to enhance the environmental sustainability of this process. Still, a limited number of case studies exist that take into account the process and utilities. Furthermore, production steps such as transportation should be included as it makes up the main philosophy of the LCA, which is applied to the petroleum refining process. Examples of such include the environmental impact assessment and its minimization in a refinery [1] as well as an ontology-enhanced LCA of an oil refinery [2]. Nevertheless, not a single study in the literature combines the exergetic method and LCA to enhance the sustainability of the industrial petroleum refining processes. This paper presents the first view on the application of an exergetic LCA to the petroleum refining process and the added benefit it can bring. In this regard, this work is based on the CExD indicator [3], and the objective is to pave the way towards an environmentally sustainable petroleum refining process. Unlike the existing studies on the life cycle of the petroleum refining process, this research emphasizes the utility systems such as the power generation system. Furthermore, the scenario starts with a short-term solution such as the so-called clean fossil energy (e.g. natural gas), and then present scenarios where the renewables are added to the power mix in a stepwise approach to avoid any perturbation in the system. Crude oil distillation systems are among the largest energy consumers in chemical industries. Consequently, the recovery of relatively small quantities of heat can accumulate to become significant energy savings. One of the most efficient ways to reduce energy consumption towards sustainability is to remove the bottlenecks of the existing process plants. Generally, the best debottlenecking occurs via improved heat recovery systems through the retrofitting of the heat exchanger network (HEN). In fact, the retrofitting of the HEN in crude

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oil distillation systems are complex as they interact strongly with the associated heat recovery systems. This is also one of the main reason there has been a continuous effort to improve the efficiency and yield of the distillation unit over the years. To study the crude oil distillation connected to a set of heat exchangers, pinch analysis [4-6] and its recent extensions are most often used as they offer an effective and practical method for designing the HEN for new and retrofit projects. Moreover, the use of pinch analysis in this kind of process is appropriate for such a study as it is particularly helpful in analyzing the effect of utility and inter-unit integration. The crude oil distillation systems [7,8] already feature a high degree of energy recovery with a significant amount of integration between the process units and the utility systems, as well as between different process units.

This paper begins with asset of information regarding the database and process constraints, after which the LCA of the petroleum refining process is presented. Following that, the exergetic and ReCiPe-based diagnosis of the entire process is given. Then, we defined a set of scenarios and assessed them in terms of environmental impacts to enhance the environmental sustainability aspects of the process.

## 2. Data and methods

### *2.1. Process data*

#### *2.1.1. Process description*

This refinery [9] is comprised of 14 units and 10 utility units including crude and vacuum distillation units with products such as off gas, naphtha, kerosene, gasoline, light diesel, heavy diesel, atmospheric gas oil, and residue. More specifically, it produces 2,450 $m^3$/day of kerosene, 2,225 $m^3$/day of gasoline, and 4,811 $m^3$/day of gas oil. The crude oil feed is a mixture of 50% Ahwaz crude oil and 50% Cheleken crude oil whose distillation curve data associated with bulk properties given in Tables 1-3.

**Table 1.** Distillation data and bulk spec of the feed

| Distillation data for feed composition (TBP) | | Bulk specifications | |
|---|---|---|---|
| % Distilled | Temperature (°C) | | |
| 2 | 6.653 | Act. density (Kg/$m^3$) | 844.3 |
| 5 | 61.607 | Viscosity (CP) | 8.73 |
| 10 | 95.54 | Molecular weight | 223.7 |
| 30 | 211.562 | Std. API | 34.7 |
| 50 | 305.455 | Std. Sp. Gr. | 0.8515 |
| 70 | 426.014 | UOPK | 11.9 |
| 90 | 698.512 | CP (kJ/kg.°C) | 1.858 |
| 95 | 932.763 | | |
| 98 | 989.74 | | |

**Table 2.** Properties of the Ahwaz crude oil (API=31.4)

| TBP Distillation | | Component | | Mid. Vol.% | |
|---|---|---|---|---|---|
| Liq. Vol.% | Temp.(F) | Light Ends Analysis | Liq. Vol. Frac | API Gravity Curve | Gravity |
| 6.8 | 130 | Methane | 0.001 | 5 | 90 |
| 10 | 180 | Ethane | 0.0015 | 10 | 68 |
| 30 | 418 | Propane | 0.009 | 15 | 59.7 |
| 50 | 650 | Isobutane | 0.004 | 20 | 52 |
| 62 | 800 | N-Butane | 0.016 | 30 | 42 |
| 70 | 903 | 2-Methyl-Butane | 0.012 | 40 | 35 |
| 76 | 1000 | N-Pentane | 0.017 | 45 | 32 |
| 90 | 1255 | | | 50 | 28.5 |
| | | | | 60 | 23 |
| | | | | 70 | 18 |
| | | | | 80 | 13.5 |

**Table 3.** Properties of the Cheleken crude oil (API=34.8)

| **TBP Distillation** | | **Light Ends Analysis** | | **API Gravity Curve** | |
|---|---|---|---|---|---|
| **Liq. Vol.%** | **Temp.(F)** | **Component** | **Liq. Vol. Frac** | **Mid. Vol.%** | **Gravity** |
| 6.5 | 120 | Water | 0.001 | 2 | 150 |
| 10 | 200 | Methane | 0.002 | 5 | 95 |
| 20 | 300 | Ethane | 0.005 | 10 | 65 |
| 30 | 400 | Propane | 0.005 | 20 | 45 |
| 40 | 470 | Isobutane | 0.01 | 30 | 40 |
| 50 | 550 | N-Butane | 0.01 | 40 | 38 |
| 60 | 650 | 2-Methyl-Butane | 0.005 | 50 | 33 |
| 70 | 120 | N-Pentane | 0.025 | 60 | 30 |
| 80 | 200 | | | 70 | 25 |
| 90 | 300 | | | 80 | 20 |
| 95 | 400 | | | 90 | 15 |
| 98 | 470 | | | 95 | 10 |
| 100 | 550 | | | 98 | 5 |

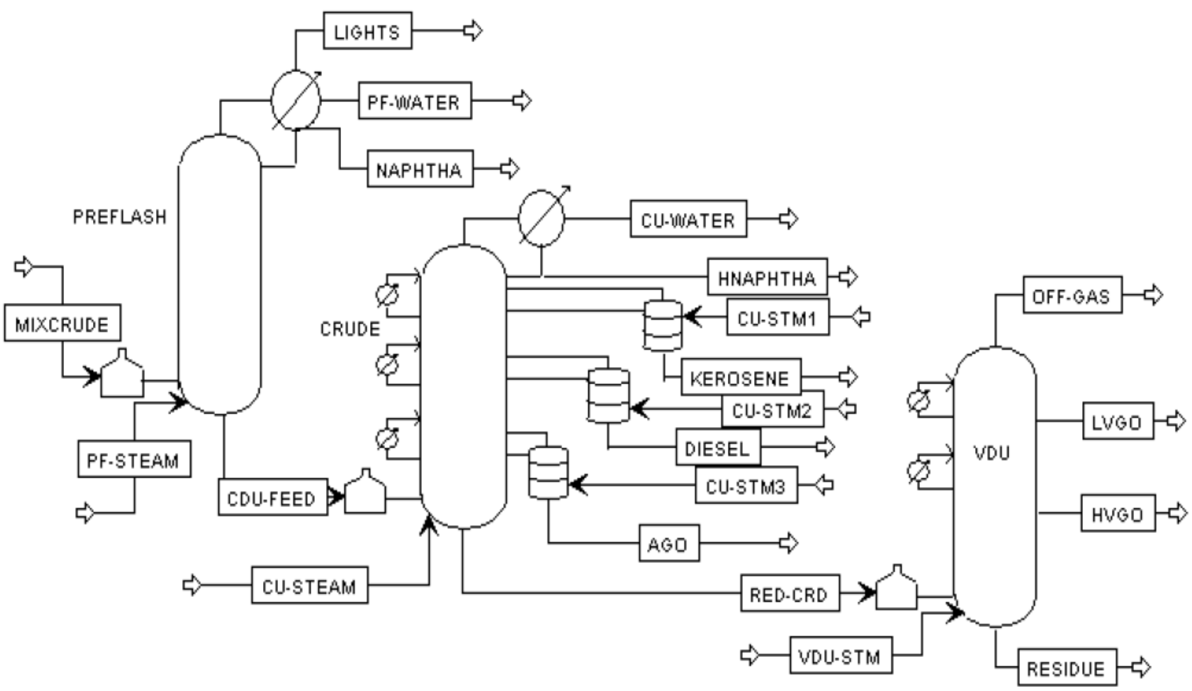


**Fig. 1.** Distillation process flowsheet

The HEN of the distillation process, described in Figure 1, includes three blocks: crude preheat exchanger network, atmospheric, and vacuum distillation.

*2.1.2. Data extraction*

The requirements of the process stream data for pinch analysis consists of the supply ($T_s$) and target ($T_t$) temperatures, the heat capacity flow rates (CP) and the heat transfer coefficients (h) of the streams. Table 4 reports the operating conditions of the atmospheric and vacuum distillation towers, flash and stripper.

*2.2. LCA data*

The process under consideration produces 0.52518 L of gasoline, 0.24414 L of diesel, and 0.10881 L of kerosene from 1 kg of crude oil as the main feed. This case study is based on the "U.S. Life Cycle Inventory (LCI) Database" administered by the National Renewable Energy Laboratory [10] in order to model the system in OpenLCA [11], an open-source licensed LCA software package. In this database, the ecoinvent [12] impact assessment methods are inserted, and the NREL flows to the impact assessment methods are linked.

## 3. Results and discussion

### *3.1. Scoping and diagnosis*

#### *3.1.1. ReCiPe*

Table 5 reports the most damaging environmental impacts. Resources - Fossil depletion with the normalized value of 1.59E-06 is at the top of the list of environmental impacts. The human health-total with the normalized quantity of 3.74E-07 is the second most damaging environmental impact. Human health - human toxicity with the normalized value of 2.07E-07 is the third most damaging environmental impact. Human health - climate change is in fourth place with the normalized quantity of 1.08E-07, followed by human health - particulate matter formation (5.85E-08). Also, note that the ecosystems-total has the value of 9.24E-09.

**Table 4.** Operating conditions of atmospheric and vacuum distillation towers, flash and stripper

| Parameter | TV-101 Crude flash drum | TV-102 Crude column | TV-151 Vacuum column | TV-105 Naphtha stripper | TV-116 Kerosene stripper | TV-106 Atm gas oil stripper |
|---|---|---|---|---|---|---|
| **Pressure at top (kg/cm$^2$)** | 4.6 | 1.4 | -0.999 | 2 | 2.1 | 2.2 |
| **Pressure at bottom (kg/cm$^2$)** | 4.6 | 2.3 | -0.972 | - | - | - |
| **Number of trays** | - | 51 | 5 | 5 | 8 | 5 |
| **Reboiler duty (kW)** | - | - | - | 1300 | 2790 | - |
| **Steam demand (kg/hr)** | - | 5000 | - | - | - | 3000 |
| **Distillate flowrate (kg/hr)** | 8713 | 100728 | 729 | 11745 | 12057 | 32247 |

#### *3.1.2. CExD*

Based on the CExD findings reported in Table 6, the total environmental impact of the base case already analyzed is equivalent to0.10539 MJ of the on-renewable energy resources. Table 6 identifies the units that cause the environmental impacts based on CEXD. The crude oil production unit (99.29%) is at the top of the list followed by the steam generation system supplied by natural gas (0.72%) and the electricity generation system supplied by residual fuel oil (0.03%), thus stressing the contribution of utilities in damaging the environment.

**Table 5.** Normalized results of ReCiPe for the base case

| Impact category | Amount |
|---|---|
| Resources-total | 1.59E-06 |
| Resources - Fossil depletion | 1.59E-06 |
| Human Health-total | 3.74E-07 |
| Human Health - Human toxicity | 2.07E-07 |
| Human Health - Climate Change | 1.08E-07 |
| Human Health - Particulate matter formation | 5.85E-08 |
| Ecosystems-total | 9.24E-09 |
| Ecosystems - Climate Change | 9.13E-09 |
| Ecosystems - Terrestrial acidification | 7.19E-11 |
| Human Health - Photochemical oxidant | 3.55E-11 |
| Ecosystems - Freshwater ecotoxicity | 3.14E-11 |
| Ecosystems - Marine ecotoxicity | 6.36E-12 |
| Ecosystems - Terrestrial ecotoxicity | 2.15E-12 |
| Human Health - Ozone depletion | 4.53E-14 |

**Table 6.** Main contributing processes to CExD Contribution

| | Process | Amount |
|---|---|---|
| 99.29% | Crude oil, at production | 0.10464 |
| 0.72% | Natural gas, combusted in industrial boiler | 0.00076 |
| 0.03% | Electricity, residual fuel oil, at power plant | 3.63E-05 |
| 0.02% | Transport, ocean freighter, average fuel mix | 2.31E-05 |
| 0.02% | Residual fuel oil, combusted in industrial boiler | 2.24E-05 |
| 0.00% | Liquefied petroleum gas, combusted in industrial boiler | 5.42E-07 |
| 0.00% | Transport, barge, average fuel mix | 1.05E-08 |

### *3.2. Sustainability enhancement of HEN*

Having evaluated the life cycle of the petroleum refining process, the main source of damage to the environment is the crude oil production unit and consequently, the HEN. Therefore, it is necessary to define scenarios where the HEN has undergone retrofitting.

#### *3.2.1. Existing HEN*

The process has 21 hot and 10 cold streams, shown in Figure 2. Furthermore, the process has 18 process-to-process heat exchangers, 22 cold utility exchangers and 4 hot utility exchangers, represented in Figure 2.

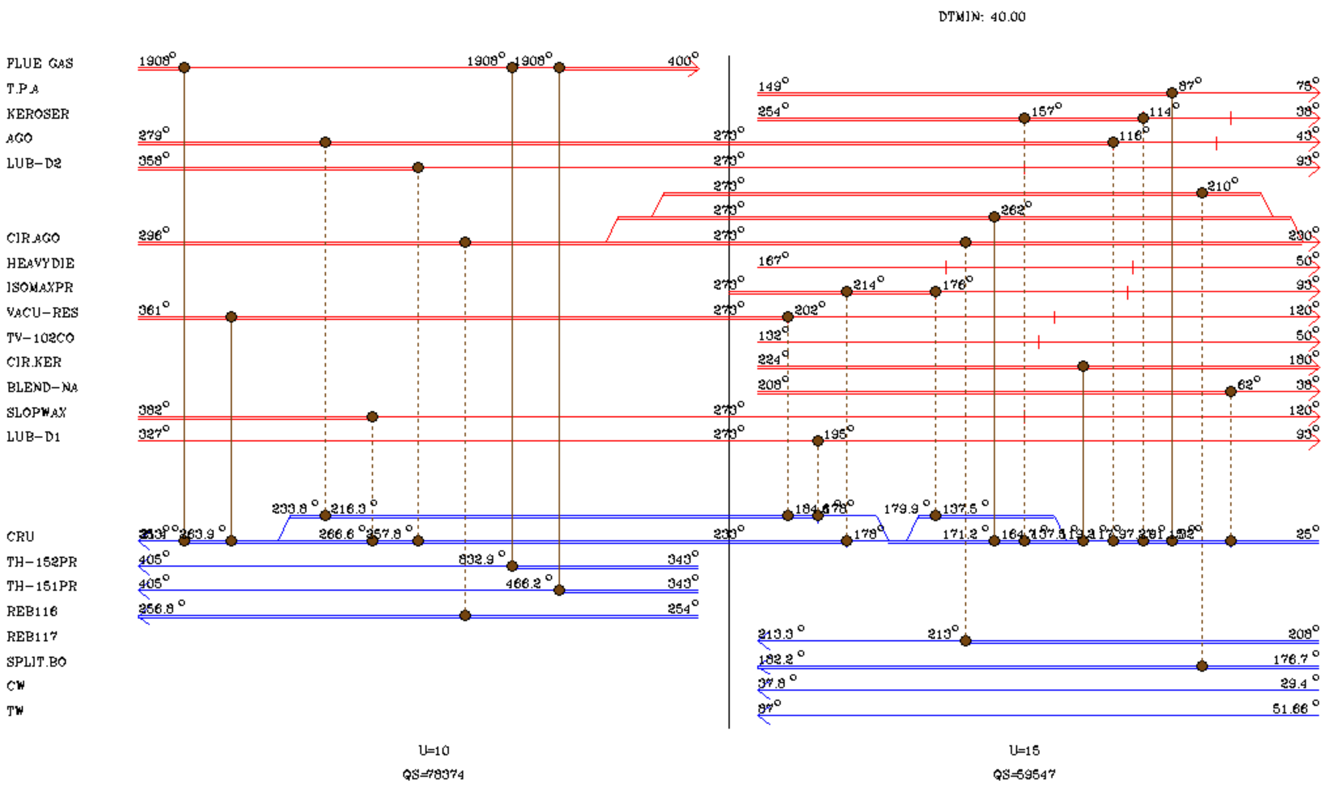


**Fig. 2.** Grid diagram of existing heat exchanger network

The cold utilities exchangers include 11 water and 11 air coolers. The hot utilities consist of four fired heaters. The flue gas requirement is 78.4 MW as the hot utility. The cold utilities consist of CW 4.03 MW (9.5٪), TW 13.27 MW (31.3٪), and cooling air 25.07 MW (59.1٪). Nevertheless, the EMAT of the existing HEN from the profile temperatures is roughly40 °C for process-process exchangers. The total area for the HEN energy is 12,609.32 m$^2$. The minimum or optimum values of $\Delta T_{min}$, based on the A1-1 exchanger, are found to be 8.02°C and 21.12 °C for A1-2 heat exchangers. As the effective temperature difference is reduced, due to the higher capital costs for the extra area, the A1-2 cost is commonly higher than the A1-1 cost (Figures 3 and 4).

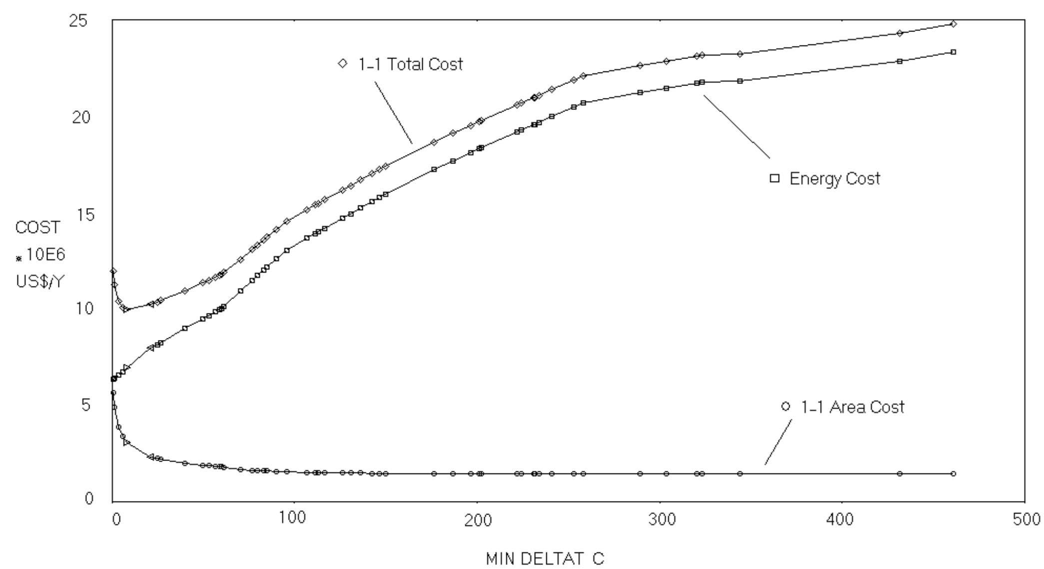


**Fig. 3.** Range target plot of total annualized cost (A1-1) showing the optimum $\Delta T_{min}$ and variation of energy and capital cost with $\Delta T_{min}$

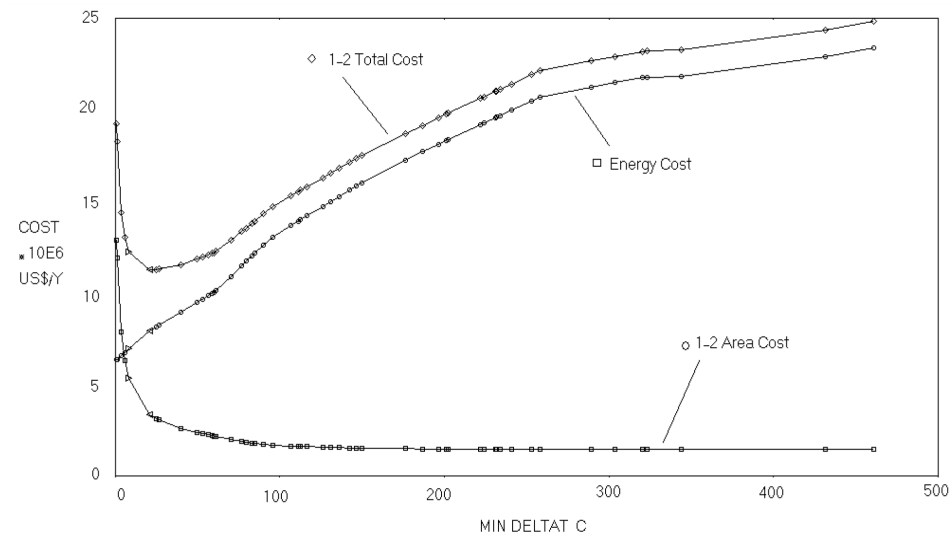


**Fig. 4.** Range target plot of total annualized cost (A1-2) showing the optimum $\Delta T_{min}$ and variation of energy and capital cost with $\Delta T_{min}$

Concerning the determination of $\Delta T_{min}$ for the retrofit design, the energy area plot of the existing process in Figure5shows that the existing HEN has an area efficiency of 0.7254, where the existing and target areas for the existing process-to-process network energy recovery are 9,077.14 and 6,584.56 $m^2$, respectively. Regarding all the exchanger units, the total number of shells is 43 and the average area per shell is 293 $m^2$, whereas the number of shells for the only process-to-process exchangers becomes 29 and the average area per shell becomes 313 $m^2$. Consequently, the average size of the exchanger shell of the existing HEN is nearly300 $m^2$. On the subject of the cost of the energy target, the hot utility cost is 71.23 $/kWy and the cold utility cost is 16.116 $/kWy, but the investment cost is 1.5×$10^6$. Concerning the calculation of energy saving and investment, the assumptions recommended in the literature (Al-Riyami et al. – 2001) are used. Figure 6 shows that the optimum approach temperature is 18.96 °C. The energy targets of process at this optimum value are $Q_{H\ min}$ = 68,661.40 MW and $Q_{c\ min}$ = 49,834.89 MW with a scope for energy savings of 9738.6 KW as the hot and cold pinch temperatures are 273.14 °C and 254.15 °C, respectively. Concerning the area target for the retrofit design, it is calculated using the constant and incremental α. The minimum area target for incremental α is 10,000 $m^2$, the incremental area is 3415.35 $m^2$, and the area target of design of incremental area is 12,492.49 $m^2$. In contrast, the extra- required area for constant αis 4708.23 $m^2$ and the area target of design is 13785.37 $m^2$.

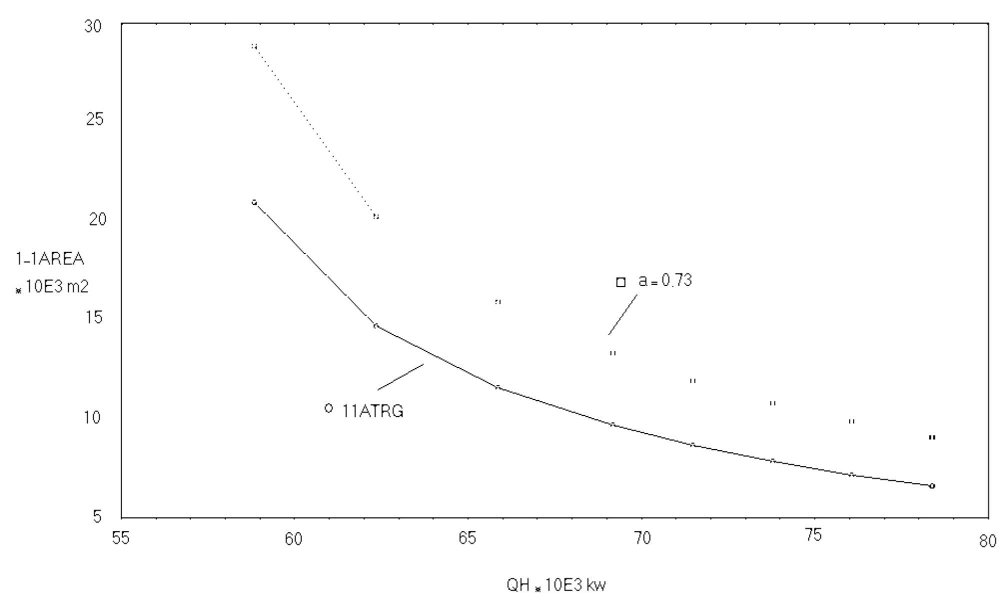


**Fig. 5.** Energy area plot of the distillation unit HEN showing the location of the existing network relative to the ideal target

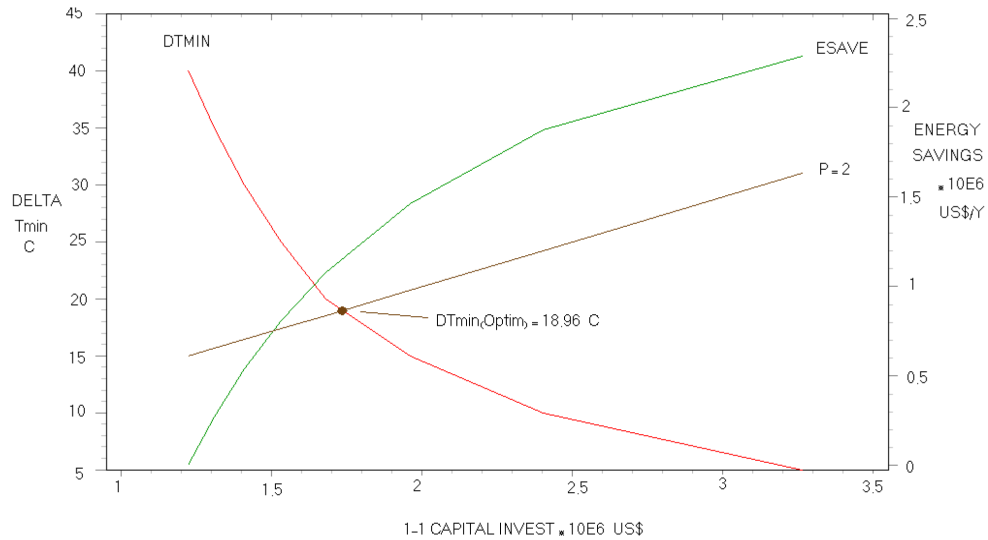


**Fig. 6.** Energy savings vs. investment and $\Delta T_{min}$ vs. investment plot

Moreover, the evaluation of the existing network determines the heat flow violation of the pinch as summarized in Table 7.

**Table 7.** Cross pinch heat transfer penalties (kW)

| Exchanger | Heat transfer (kW) |
|---|---|
| TE-160 | 1174.90 |
| TE-107 | 1516.22 |
| TE-165 | -114.030 |
| TE-119 | 494.294 |
| TE-164 | 1479.69 |
| TE-163 | 0.772727 |
| TE-106 | 10.7797 |
| TE-117 | 230.920 |
| TE-105 | 713.753 |
| TE-184 | 1154.60 |
| Sum | 6661.89 |

*3.2.2. Retrofit HEN*

The optimum energy recovery corresponds to a minimum approach temperature of 18.96 °C, and the minimum energy consumption of the process is given by the composite curves. In the diagnosis stage, to increase the energy recovery of the existing HEN constrained by a bottleneck in the process, known as the network pinch, and overcome the bottleneck, topology can be changed. The modifications which increase energy saving by shifting heat from below to above the network pinch; consist of resequencing, repiping and the addition of new heat exchangers. As the area efficiency method is used for targeting, the optimum value of the minimum approach temperature (18.96 °C) is used for the retrofit design in this study. The design objective in the diagnosis phase is set for minimum energy consumption. *Design option A:* Resequencing creates one beneficial option leading to a 3,036 kW heat demand reduction as reported in Table 21. As there is no more beneficial resequencing modification, repiping is taken into account. The benefit of the first alternative can result in 1,130 kW heat demand reduction, while the second one to 389 kW. The next alternative involves the addition of a new heat exchanger that identifies options which presents a 3,951 kW energy saving in total. Tables 21-23 show the steps taken for the design options and provides details of the parameters at each modification. Design option A, with a total hot energy usage of 36,365 kW, needs a 16,115 m$^2$ surface area in 38 exchangers thatrequires3, 506 m$^2$ less surface area compared with the existing network. Note that when the hot utility load of 36,365 kW is compared with the target value of 36,349 kW, it leads to a 15 kW difference that is relatively very low. *Design option B:* Repiping creates one beneficial option leading to a 1,703 kW heat demand reduction as reported in Table 22. The addition of the new heat exchanger generated one beneficial alternative that gives a 2,183 kW energy savings. Repiping generated one beneficial option that results in a426 kW heat demand reduction. The next modification for this design option is the addition of new heat exchanger that leads to a total energy savings of 3,512 kW. Design option B, with a total hot energy usage of 109,048 kW that is the same as existing one, needs 17,873 m$^2$ surface area in 38 exchangers which requires 2,914 m$^2$ less surface area in relation to the existing network. Note that a comparison of the hot utility load of 109,049 kW with a target of 36,349 kW means a difference of 72,699 kW. *Design option C:* The addition of a new heat exchanger generated five favorable alternatives, which offer 9,203 kW of energy savings in total as reported in Table 23. Repiping generated one advantageous option leading to a 128 kW heat demand reduction. Design option

C with a total hot energy usage of 109,048 kW, the same as the existing one, needs an18, 629 m$^2$ surface area in 38 exchangers, which requires 3,706 m$^2$ less surface area in relation to the existing network. Note that the hot utility load of 109,049 kW can be compared with the target with a value of 36,349 kW to show 72,699 kW as the difference. The comparison of the results of the design options together with the existing design and hot utility load are given in Table 8. A comparison of the different alternatives shows that design B presents the best retrofit option having the largest difference in hot utility and the smallest extra area required. The addition area required for the existing exchangers can be reduced by carrying out heat transfer enhancement technique analysis (Wadekar and Stehlik, 2000; Zhu et al. 2000). All the design options have five new heat exchangers added to them.

**Table 8.** Comparison of design options parameters with targets and existing design

| Design | Hot utility load (kW) | | | Area (m$^2$) | | No of units |
|---|---|---|---|---|---|---|
| | Used | Target | Difference | Used | Difference | |
| **Existing** | 109048.6 | 36349.5 | 72699.1 | 12609.32 | 0 | - |
| **Design option A** | 36365.3 | 36349.5 | 15.7622 | 16115.6 | 3506.28 | 38 |
| **Design option B** | 109048.6 | 36349.5 | 72699.1 | 17873.14 | 2914.62 | 38 |
| **Design option C** | 109048.6 | 36349.5 | 72699.1 | 18629.66 | 3706.14 | 38 |

### *3.3. Sustainability enhancement of the power generation unit*

#### *3.3.1. Scenario definitions*

Having assessed the life cycle of the petroleum refining process, the power generation unit is the most negative block and the main source of the damage to the environment. Therefore, it seems appropriate to define scenarios where this unit has undergone retrofitting. Based on the literature [13,14], the first alternative is dedicated to a change from residual fuels to natural gas for power generation systems. The second alternative also concerns the power generation system and suggests using only renewable sources for power generation systems.

#### *3.3.2. Environmental sustainability assessment of scenarios*

The results of the environmental sustainability assessment for each type of the electricity generation scenarios are given in Figures 7 and 8; the following section will investigate the impact of each one.

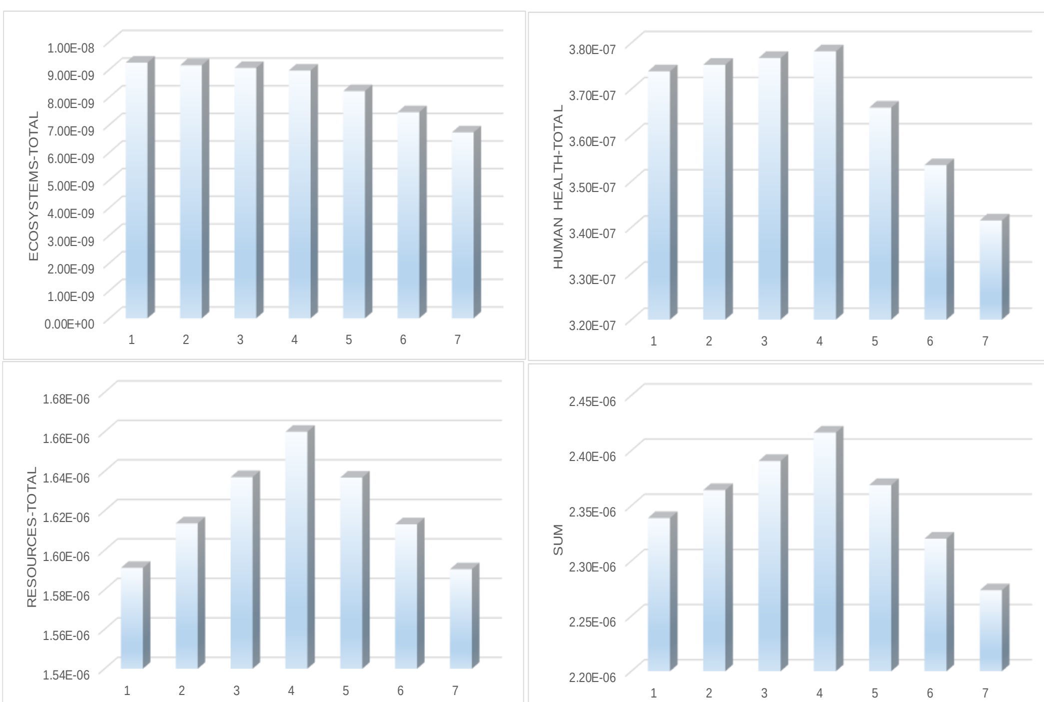


**Fig. 7**. Impact categories of Ecosystems, Human Health, and Resources for the scenarios based on ReCiPe

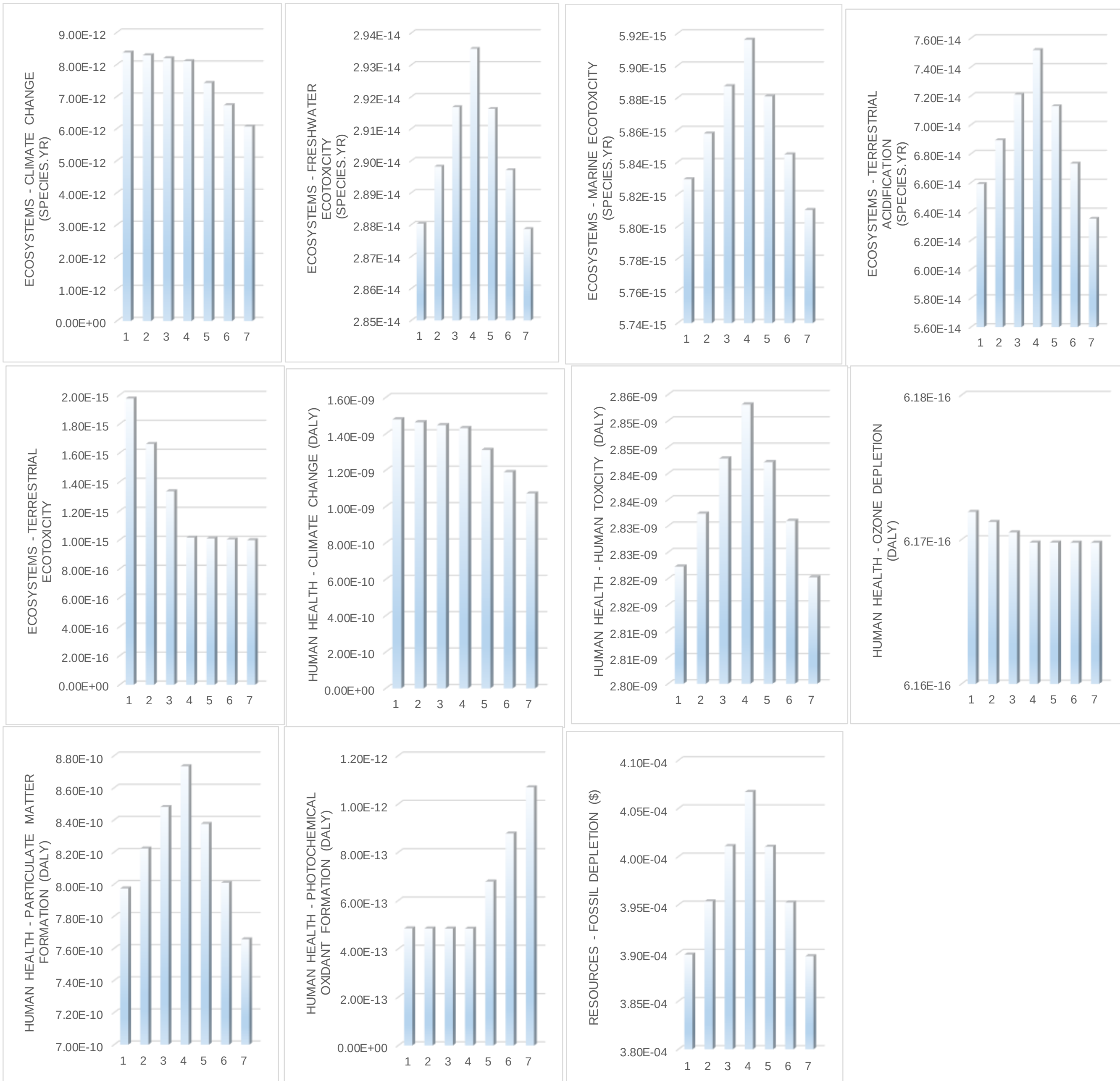


**Fig. 8**. Impact subcategories of Ecosystems, Human Health and Resources

*3.3.2.1. Ecosystems*

Climate change: As shown in Figure 8, option 1 has the highest climate change impact (8.38E-12 species.yr) followed by option 2 (8.29E-12 species.yr). This impact for the base case is primarily due to the emission of $CO_2$ and methane. Option 7 is the most advantageous alternative for this indicator with a value of 6.07E-12 species.yr. *Freshwater ecotoxicity:* As depicted in Figure 8, the impact of freshwater ecotoxicity shows a different trend than the climate change impact: natural gas power is the worst choice with 2.94E-14 species.yr. This quantity is one order of magnitude more than the renewables and even the residual fuel oil power. For example, the impact from residual fuel oil power in option 1 is 2.88E-14 species.yr; this is mainly due to the discharges of barium and silver.

*Marine ecotoxicity:* As can be observed in Figure 8, the ranking of the possibilities for this environmental impact is the same as for freshwater ecotoxicity. In other words, option 4 is more severe than any other possibility with an impact of 5.92E-15 species.yr followed by option 3 with 5.89E-15 species.yr. The impact from the other alternatives hasthe same orders of magnitude, with the biomass power being the best route at 5.81E-15 species.yr. The main reason for the high impact from the fossil fuel technologies, such as the base case, is the discharge of barium and silver. *Terrestrial acidification:* As demonstrated in Figure10, option 4 is the most unbearable option for this indicator, with a value of 7.52E-14 species.yr. Terrestrial acidification for the base case is chiefly a consequence of the release of sulfur oxides, nitrogen oxides, and sulfur oxides. *Terrestrial ecotoxicity:* As displayed in Figure 8, the base case is significantly worse than any other route, with an estimated terrestrial ecotoxicity of 1.98E-15 species.yr that is mainly due to the emissions of nickel, aldehydes, cobalt, selenium and mercury; this is followed by option 2 with 1.66E-15 species.yr. The biomass power is the most advantageous alternative with 9.98E-16 species.yr, which is one order of magnitude more than the natural gas power (1.02E-15 species.yr).

*3.3.2.2. Human Health*

*Climate change:* As shown in Figure8, the biomass power choice has the lowest climate change impact, assessed at 1.07E-09 DALY. The gas power is estimated to generate 1.43E-09 DALY, which makes it the worst possibility among the alternative sources of energy. However, the residual fuel oil power is significantly more severe than any other routes, with an estimate of 1.48E-09 DALY; it is followed by option 2 with 1.46E-09 DALY and option 3 with 1.45E-09 DALY. For the base case, the majority of climate change is a result of the release of $CO_2$ and methane.

*Human toxicity:* As presented in Figure8, the trend of human toxicity is completely different from climate change. Option 4 is the most unpleasant alternative for this indicator, with a value of 2.85E-09 DALY. For the base case, it is largely a consequence of the emissions of barium. The most sustainable preference is biomass power with a human toxicity of 2.82E-09 DALY.

*Ozone depletion:* As presented in Figure 8, all the options result in the same impact regarding this indicator with a value of 6.17E-16 DALY. This impact for the base case is largely due to the release of methane (dichlorodifluoro-, CFC-12), ethane (1,1,1-trichloro-, HCFC-140) and methane (tetrachloro-, R-10).

*Particulate matter formation:* As depicted in Figure8, the impact of particulate matter formation shows the same trend as those of human toxicity: the gas power is the worst choice with 8.73E-10 DALY. For the base case, it is mainly owing to the discharges of sulfur dioxide, nitrogen oxides, sulfur oxides, sulfur dioxide and particulates between 2.5 and 10 µm.

*Photochemical oxidant formation:* As discussed earlier, although common sense deems scenario 5 as more sustainable than scenario 4, the LCA results in terms of photochemical oxidant formation proves inverse. Taking into account all impacts and according to the LCA, scenario 5 is more sustainable than scenario 4. However, in terms of photochemical oxidant formation criterion, Figure 8 shows that scenario 4 causes less damage to the environment than scenario 5. The large majority of this impact for the base case is largely is due to the emissions of nitrogen oxides, non-methane volatile organic compounds, CO, sulfur oxides, and sulfur dioxide.

*3.3.2.3. Resources*

*Fossil depletion:* As shown in Figure 9, option 4 has the highest fossil depletion (4.07E-04 $) followed by options 3 and 5 (4.01E-04 $). This impact for the base case is primarily due to the flow of crude oil and natural gas. The biomass power is the best alternative for this indicator with a value of 3.90E-04 $. In other words, as expected, the depletion fossil resources are highest for the fossil-fuel power generation units with 3.90E-04 $ for the residual fuel oil and 4.07E-04 $ for the natural gas. By comparison, the depletion of fossil resources for the renewable routes is almost equal to the options based on the residual fuel oil. The totally renewable route (scenario 7) and option 1 result in almost the same impact of 3.90E-04 $. Likewise, 67% of the renewable resource option (scenario 6) and option 2 result in the impact of 3.95E-04 $.

## 4. Conclusions

The incremental area efficiency methodology is used for the targeting stage of the design, and the design is carried out using the network pinch method. The existing hot utility consumption of the process is 78.4 MW with a ΔT 40°C. The results of this retrofit study demonstrated that for a grass root design, the optimum approach temperature is 8.02 °C, whereas it is 18.96 °C for the retrofit design, thereby establishing the scope for potential energy savings. The area efficiency, α, of the existing network is 0.7254, which points out that the existing design used the area reasonably efficiently. To achieve a practical project, the number of modifications is limited. The modifications include the addition of new heat exchanger units and repiping of the existing exchanger. Comparison of the results of the design options together with the existing design and hot utility load shows that design option B gives the best retrofit alternative. It has the largest difference for hot utility and the smallest extra area required which is selected for retrofit to enhance the sustainability aspects of the existing technology. Design option B with a total hot energy usage of 109,048 kW, which is the same as the existing one, needs a 17,873 $m^2$ surface area in 38 exchangers which requires 2,914 $m^2$ less surface area compared with the existing network. The additional area required for the existing exchangers can be reduced by carrying out heat transfer enhancement technique analysis. In addition, the LCA helps to identify and propose solutions that can save energy and natural resources used to produce gasoline. As an example, the total environmental impact of the petroleum refining process cannot be reduced from 1.05E-01 MJ-Eq according to CExD but it can be reduced from 2.34E-06 to 2.27E-06 according to ReCiPe by switching from residual fuel oil to biomass. Therefore, the proper choice of the energy mix among the available energy sources helps to increase the environmental sustainability. The LCA quantifies the environmental impact of each scenario to enable us to evaluate each modification on the sustainability of the petroleum refining process. More precisely, the first step of transitioning towards sustainability involves replacing residual fuel oil with natural gas, as a so-called clean energy; this leads to sustainability enhancement only in terms of climate change (ecosystems and human health), terrestrial ecotoxicity, and ozone depletion. However, it does not result in the overall sustainability augmentation according to CExD and ReCiPe. This emphasizes the importance of LCA in quantifying each impact compared to the biased analysis, as this quantitative trend in sustainability diminution is not expected at the beginning. In other words, prejudgments can present natural gas as a less damaging energy source compared to fuel oil. Nevertheless, LCA shows that natural gas can be even less sustainable than the residual fuel oil from the perspective of freshwater ecotoxicity, marine ecotoxicity, terrestrial acidification, human toxicity, particulate matter formation, and fossil depletion impacts; thus, it brings into question the sustainability of natural gas power.

## Nomenclature

| Abbreviation | Description |
|---|---|
| BM | Biomass |
| BOD | Biological Oxygen Demand |
| CC | Climate Change |
| CEC | Cumulative Exergy Consumption |
| CED | Cumulative Energy Demand |
| CML | Centre Of Environmental Sciences - Leiden University |
| COD | Chemical Oxygen Demand |
| DALY | Disability-Adjusted Life Years |
| EM | Energy Mix |
| EQ | Ecosystem Quality |
| ES | Ecosystems |
| FD | Fossil Depletion |
| FE | Freshwater Ecotoxicity |
| HH | Human Health |
| HT | Human Toxicity |
| LCA | Life Cycle Assessment |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |
| MARPOL | Marine Pollution – The International Convention of Pollution from Ships – International Maritime Organization |
| MCS | Monte Carlo Simulation |
| ME | Marine Ecotoxicity |
| NG | Natural Gas |
| NMVOC | Non-Methane Volatile Organic Compounds |
| OD | Ozone Depletion |
| PG | Power Generation |
| PMF | Particulate Matter Formation |
| POF | Photochemical Oxidant Formation |
| ReCiPe | *RIVM (RijksinstituutvoorVolksgezondheiden* Milieu) and Radboud University, Centre of Environmental Sciences - Leiden University, and PRé Consultants |
| RES | Resources |
| RFO | Residual Fuel Oil |
| SY | Species.yr |
| TA | Terrestrial Acidification |
| TE | Terrestrial Ecotoxicity |
| VOC | Volatile Organic Compounds |

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