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Economic Assessment of Heat Exchanger Network Retrofit Options Based on Historical Data of Energy Price Trends

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Energy-saving retrofit of industrial plants is one of the vehicles of decarbonisation and the goal of modern society. The retrofit of the heat exchanger network allows saving a large amount of primary energy across units and industrial clusters. Usually, selecting suitable retrofit options is a big challenge for decision-makers that impacts future plant profit and environmental issues. This research proposes assessing different retrofit options of crude oil distillation unit based on historical data of energy prices. Periods with different energy price trends were analysed, accounting for the retrofitted unit start-up after the first and third year. The impact of energy price dynamics on economic and environmental benefits of different retrofit option was analysed. The sustainability of the most economically beneficial option was assessed across different energy price trends. The overdetermined/lost benefits of all options were calculated, allowing the decision-maker to proceed with the most appropriate one.

1. Introduction

The problem of assessing the benefits and risks of the retrofitting of existing heat exchange networks (HEN) has been studied for a long time. Jegede and Polley (1992) pointed out the need to determine the final characteristics of networks before starting design. The correct distribution of the heat transfer area between heat exchangers leads to the largest savings, including energy resources. Nevertheless, predicting the dynamics of the energy market, which depends on the price of crude oil, remains. Many current forecasts are based on well-known econometric models. For example, Hao et al. (2020) suggest using a regularisation constraint. Safari and Davallou (2018) rely on hybrid models that improve forecast accuracy and take into account the nonlinearity of changes in the global economy.

Depletion of energy resources inevitably leads to a price increase. It affects a selection of the retrofit approach of existing HENs and the principles of the new design. Nordman and Berntsson (2001) developed a method for HEN a retrofit using the Pinch analysis and a modification of the Grand Composite Curve. The technique established a correlation between the objective function curves. The results show that achievement of the required energy saving will lead to the total cost of the HEN will be higher in the case of installing utility equipment on process flows with a large value of the opposite energy potential. The study by Li et al. (2019) reports that energy and economic goals can be achieved jointly without harming investors, using Pinch-design tools, regardless of price fluctuations in the energy market.

Liu et al. (2020) argue that energy-efficient retrofits are impossible without good management of a HEN. It allows achieving minimum overspending of valuable energy resources. Jiang et al. (2020) urge to solve problems of energy and economic optimisation jointly with the environmental component. It will lead to the most profitable selected of a HEN in the long term. Thus, the feasibility study of a method for choosing an optimal retrofit project is complement by a solution to environmental problems. Zhang et al. (2020) propose a two-stage chessboard method for a HEN synthesis. This method allows you to achieve the best financial and economic criteria under given conditions. Rathjens and Fieg (2019) pay attention to minimising annual costs based on studying the structure of a HEN and stochastic factors.

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Pan et al. (2012) used the MILP model to find the optimal compromise between primary energy cost, final energy savings, and capital investment. Novak Pintarič and Kravanja (2017) show some criteria based on the discounted cash flows to help establish a compromise solution between long-term cash flow generation and profitability. The graphical tools could also be trapped in the local optimum, so the investment cost is difficult to be considered. Wang et al. (2021) developed a method based on a constrained particle swarm optimisation algorithm.

Regardless of approaches, all researchers agree that periodic retrofit of HENs is necessary for any modern industrial process. Despite up to date developments in HEN retrofit, the decision-making problem, when selecting different retrofit option, is still actual. Considering a dynamic fluctuation of energy cost, the retrofit of HENs makes possible a selection of the optimal configuration of a network in the long term. In this work, the influence of energy cost on decision-making when retrofitting the HEN is studied based on historical data of energy price changes. The approach assesses the economic criteria of different HEN retrofit options under energy price dynamic and time of the retrofit. The novelty can be proved by investigating economic indicators of HEN retrofit under historical energy price trends and providing analysis and a specific tool for decision-making. It allows avoiding overdetermined and lost profit and help select the most appropriate retrofit option in the long term. Besides, the environmental versus economic cost or benefits can also be estimated for chosen retrofit options.

2. Methods

Sometimes, when optimising an industrial unit, several options for retrofit appear (Ulyev et al., 2018). Often, the choice of the best option is based on the main economic criteria that are calculated at a constant price for electricity and fuels. Considering the energy price dynamics allows determining the lost or overdetermined benefit for the selection of the retrofit option.

It is necessary to determine the value of energy savings and capital costs (CAPEX) for each option for retrofitting a unit. To simplify the calculation, the main cost items of the project are the equal percentage of the CAPEX (Table 1).

Table 1: The main cost items

Cost item	Percentage of the CAPEX
Engineering cost	10 %
Amortisation in the fourth year	30 %
Amortisation in the tenth year	20 %
Operating and maintenance costs	2 %

In the beginning, the amount of investments required to implement the considered retrofit option is determined. The investment is equal to the CAPEX and engineering cost. The loan is taken for a part of the investment that is not covered by private capital investments. The annual loan payment amount is calculated by Eq(1):

$$\text{rate} = \frac{LPA\cdot[LI\cdot(1+LI)^n]}{(1+LI)^n - 1} \tag{1}$$

The economic calculation for each year of the established project period is carried out according to the principle of cash flows. Cash flow is equal to the difference between receipts and payments of the company's cash for a specified period. Cash receipts are savings of utilities and electricity converted into money equivalent. The payments consist of corporate tax, annual loan payments, amortisation, operating and maintenance costs. The yearly amortisation is equal to a percentage of the total investment.

The following criteria determine the economic efficiency of the retrofit option: net present value (NPV), internal rate of return (IRR), discounted payback period (DPP).

For each year, the NPV is calculated using Eq(2):

$$NPV_i = -CF_{E.i}\cdot(1+WACC)^{-i} \tag{2}$$

However, it is necessary to know the NPV value for entire set term of the project to assess the retrofit efficiency. This value is equal to the sum of NPV for the calculated periods. The IRR and DPP are determined by fitting according to Eq(3) and Eq(4):

$$0 = \sum_{i=0}^{n} \frac{CF_{E.i}}{(1+IRR)^i} \tag{3}$$

$$DPP = M + \frac{-NPV_M}{CF_{E.M+1}} \quad (4)$$

The best retrofit option has a high rate of return (the highest IRR), fast payback (the lowest DPP), and high profit (the highest NPV).
The pre-retrofit period for the implementation of the project depends on many factors (economic capabilities) and is individual for each industry and factory. Therefore, it is necessary to consider the start of operation of a retrofitted unit in the economic calculation. For example, if the retrofit of the unit has an event for re-piping the existing equipment, then a partial retrofit carried out during the next planned repair or without stopping process. In this case, the profit from saving utilities and/or electricity during the preparatory period is possible.
External issues have the most significant impact on the economic sustainability of retrofit options of a unit. The main parameters that characterise this influence are the inflation rate and the cost of energy. The proposed approach considers inflation and the dynamics of changes in the energy price over a long period. Then, a comparison of the main economic criteria of retrofit options for different historical periods (periods of crisis: a steep rise and a drop of energy price; stable periods: a period with remain flat of energy) was performed. The economic calculation in this study is carried out considering the change in oil prices from 1861 to 2020 (Figure 1).

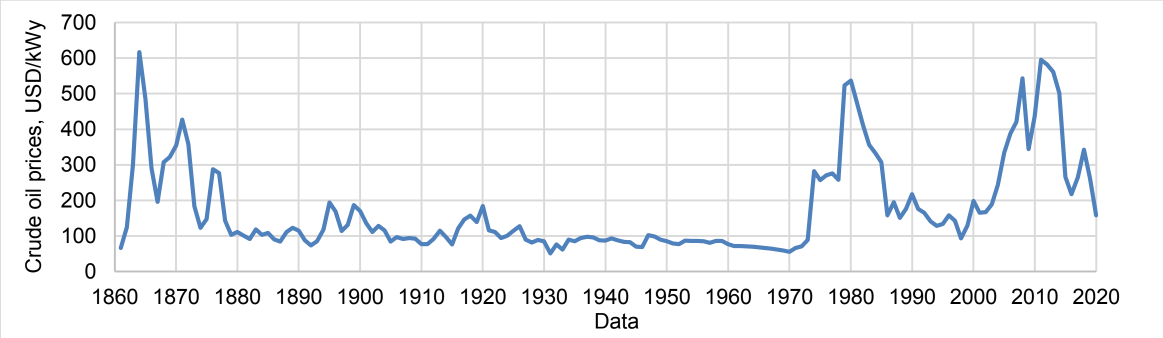

Figure 1: Dynamics of crude oil prices in the period from 1861 to 2020 (Nasdaq's Quandl, 2021)

In this study, four options for the economic analysis of the proposed retrofit options were considered:

- the cost of energy is constant over the entire time interval;
- the cost of energy changes according to historical data;
- a retrofit unit starts working after the first year of the project acceptance;
- a retrofit unit starts working after the third year of project acceptance (based on the industrial experience for typical project implementation).

In the fourth scenario, it is taken into account that the factory doesn't have energy-saving in the preparatory period, so the corporate tax amount is not calculated. In the second scenario, it is taken into account the inflation rate when converting utility savings to the money equivalent. The initial cost data is adjusted to USD 2020.

3. Case study

In this study, the calculation was made using the example of the retrofit of a crude oil distillation unit (CDU) with a nominal capacity 6 Mt/y. The unit's energy efficiency has been suggested to improve through the retrofit of the existing HEN. Three retrofit options are proposed, differing the configuration complexity, energy savings and capital costs. Table 2 shows plant data of the hot and cold utility consumption of the existing and proposed retrofit options and capital costs for retrofit.

Table 2: Data of the existing and retrofit CDU-6

Options	Furnace heat load, MW	Cold utility savings, %	Capital costs, USD
The existing unit	172.00	–	–
The retrofit option 1	101.78	38.98	9,910,821
The retrofit option 2	139.07	18.10	656,670
The retrofit option 3	151.12	11.38	1,002,646

Table 3 shows total economic data for calculating the balance of profits and cash payments.

Table 3: Initial economic data

Variable	Unit measure	Value
Bank loan (duration)	y	10
Bank loan (interest)	%	12
The annual increase in operation cost	%	1.5
Corporate taxes	%	20
The weighted average cost of capital	%	7
Private equity (% of the capital cost)	%	20

The constant energy price model was averaged and compared to the same period when energy price fluctuates. The cost of cold utility is accepted as 10 % of the cost of hot utility. Historical periods characterised by different energy prices were considered for a comparative assessment of retrofit options shown in Table 4.

Table 4: Historical periods of energy prices that are considered in this case study.

Period number	Period, y	Note
1	1861-1870	Significant fluctuations of crude oil prices
2	1951-1960	A slight change in crude oil prices
3	1961-1970	A gradual drop in prices
4	1971-1980	A rapid rise in prices
5	2011-2020	A fall in prices

4. Result and discussion

4.1 Calculation results of Scenario 1

The calculation results of scenario 1 (Figure 2a) show that retrofit option 1 has the highest NPV in all considered periods than other options. The IRR of this retrofit option indicates that the project's sustainability is high only when the cost of energy is high (periods No 1, 4, 5). It promotes levelling the negative dynamics of changes in energy prices. However, suppose the periods have a low cost of energy (period No 2) or a slight drop (period No 3). In that case, this retrofit option will be unstable if the retrofit implementation time or a loan interest rate are increased. Low sustainability can make the project economically profitless compared to other retrofit options. Therefore, retrofit option 2 is the most preferable for periods with low energy costs.

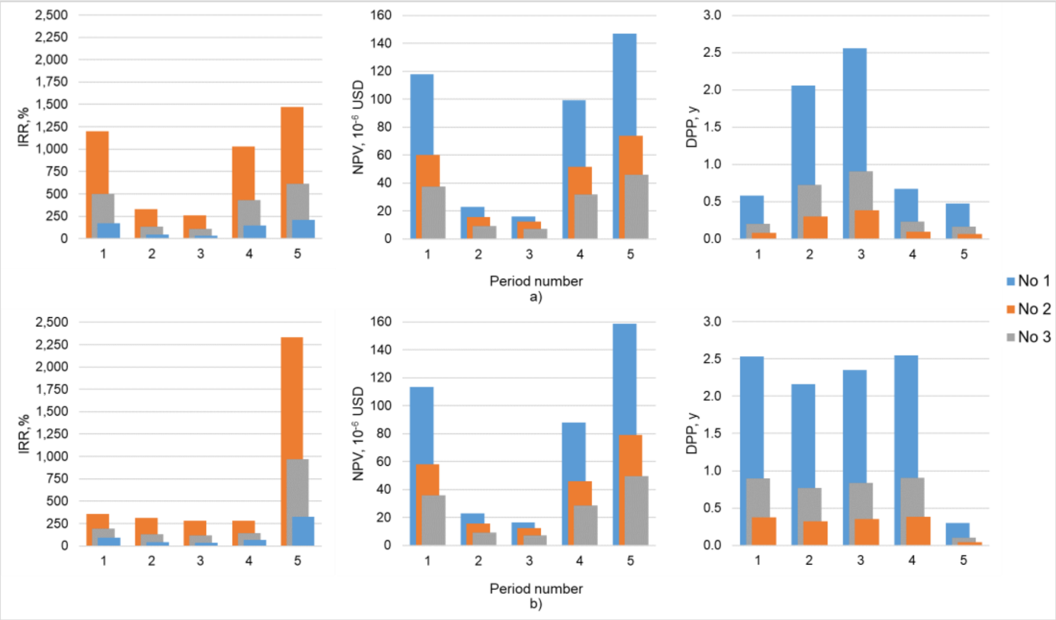

Figure 2: Economic criteria of scenario No 1, retrofitted unit operation after 1 year of the project acceptance: a) the energy price is constant; b) energy prices change.

These conclusions are also confirmed by the results of calculations, which were carried out taking into account the dynamics of changes in energy prices (Figure 2b). Comparison of NPV values calculated using models which take into account the constant and dynamic energy prices shows the first model overdetermined/lost benefits at significant fluctuations of prices (periods No 1, 4, 5). For example, the NPV of retrofit option No 1 is redetermined at 11.61·10^6 USD in period No 4, and the lost profit is 11.63·10^6 USD in period No 5. In addition, this model incorrectly determines the DPP of the project in comparison with the second model. The overdetermined or loss of profits can negatively affect the implementation of the retrofit: the emergence of expenditures, violation of the contract, and increase in the implementation period, etc. Economic criteria calculated using the first model have identical values with criteria calculation taking into account the dynamics of energy prices for periods No 2, 3. It is because of crude oil price fluctuation at about the same level during these periods. The retrofit option 3 is less stable than retrofit option 2; also, it has the lowest NPV value in the periods under consideration.

4.2 Calculation results of Scenario 2

The results of the calculation of scenario 2 (Figure 3) show that the trend of changes in economic criteria is similar to the change in economic criteria for scenario 1. However, an increase in the project implementation time in period 3 leads to a significant reduction in the NPV of retrofit option No 1. It is due to its low stability compared to other retrofit options.

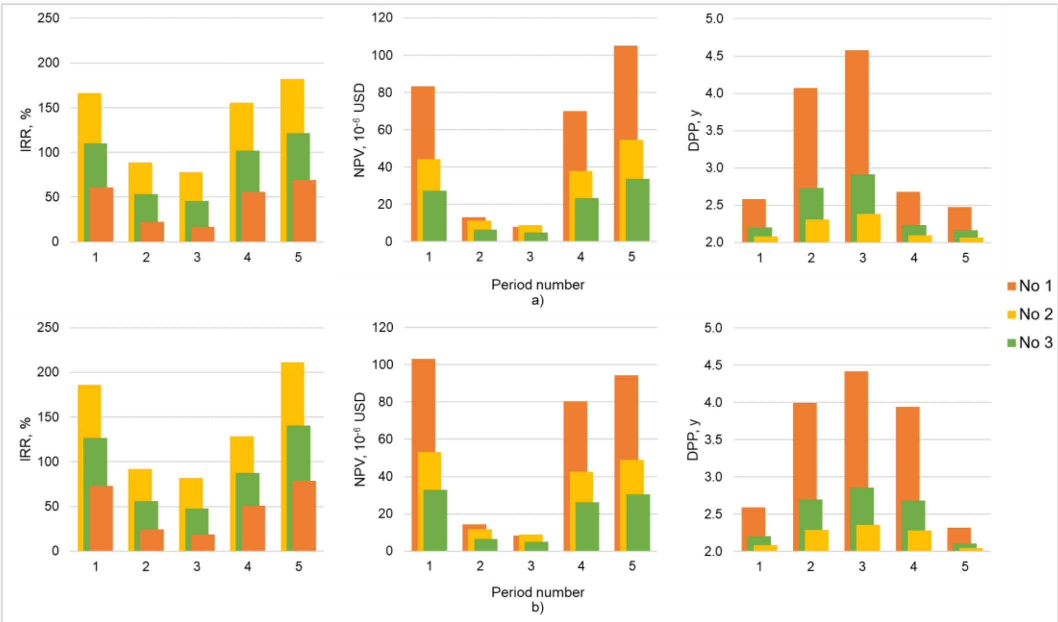

Figure 3: Economic criteria of scenario No 2 at the start work of the retrofit unit after 3 years of the project acceptance: a) the energy price is constant; b) energy prices change

If the cost of energy is low, so retrofit option 2 is the most preferable. It is due to the IRR of this retrofit option is substantially higher compared to other options. At the same time, its NPV is less than an average of 8 % compared to retrofit option No 1. The lowest DPP additionally supports the choice of this retrofit option for different periods of project implementation. The constant energy price model overdetermined/lost the benefit in periods similar to scenario 1. Longer retrofit pre-design leads to more overdetermined/loss. For example, the lost profit for retrofit option 1 is 19.74·10^6 USD in period No 1, and the NPV redetermined at 10.86·10^6 USD in period No 5.

5. Conclusions

This study presents an approach for the economic assessment of retrofit options. This approach determines economically efficient retrofit options taking into account such factors as energy price dynamics and the year when the retrofitted unit starts-up. The case study estimated the retrofit options of the HEN crude oil distillation unit. Two scenarios were considered: the start of work of the retrofitted unit after 1 year and 3 years when the project was accepted. For each scenario, an economic calculation was carried out, taking into account the statics and dynamics of the price of crude oil. Comparison of the results demonstrates the lost and overdetermined benefit and allow sustainability assessment of retrofit options across different energy price trends. The developed model makes it possible to determine an economically profitable option in the long term and estimate economic versus environmental benefits. The developed approach can also be applied to analyse both retrofit and new design of various process units (e.g. reactors, distillation columns, evaporators, etc.) in different industries. The methodology may help better analysing the potential process changes in current economic conditions and finding the best retrofit option.

Nomenclature

$CF_{E.i}$ – financial cash flow, USD
$CF_{E.M+1}$ – financial cash flow of the year during which the payback occurs, USD
DPP – discounted payback period, y
i – No of calculated year
IRR – internal rate of return, %
LI – bank loan (interest), %
LPA – investment loan, USD
M – the duration of the project until the beginning of the year in which the profit appears, year
n – project lifetime, y
NPV_i – net present value in the i^{th} year, USD
NPV_M – net present value, preceding payback year, USD
rate – annual loan payment amount, USD
WACC – weighted average cost of capital, %.

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