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Catalytic Cracking Column Scheme Modernization for Efficient Utilization of Thermal Energy

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Abstract. This paper aims to analyze options for the utilization of waste heat at oil refineries, specifically focusing on the rectification column. The study was carried out using the Aspen HYSYS software package. In this paper, two fundamentally different solutions were considered, which were modeled in the Aspen HYSYS software package, the proposed options were also compared, and their advantages and disadvantages were identified. In the first case, it is proposed to consider using the energy from the hydrocarbon stream to heat water for a hot water supply system. In the second case, it is proposed to use same initial energy stream to produce electricity by applying Rankine cycle. As a result of the study, both proposed options for waste heat utilization were recognized as economically justified. However, the feasibility of using these solutions depends significantly on the needs of a particular enterprise, on their scale, the schemes implemented on them, the operating installations composition, loads, energy consumption parameters, and other parameters.

Keywords: Aspen HYSYS; District heating; Oil refining; Organic rankine cycle; Thermal energy utilization

1. Introduction

In Russia, which ranks as the second-largest oil producer globally and the third-largest in terms of processing capacity, with over 30 oil refineries across its territory, the energy efficiency level in this industry falls below the global leaders. Therefore, it is expedient to improve technologies, upgrade and modernize equipment, as well as to introduce methods for utilizing the various hot streams heat of oil refineries (Li *et al.*, 2021). The largest oil refining companies in Russia are trying to improve the energy efficiency of the refining sector in various ways. The main energy and resource-saving directions at oil refineries include the following methods: carrying out organizational and technical measures to reduce the energy capacity of process units, the old equipment modernization and replacement with new one with higher efficiency; fuel use of technologies optimization; an increase in heat recovery by optimizing the coolant flow patterns, as well as by increasing the recuperators heat exchange area (Balzamov *et al.*, 2020; Kusumah *et al.*, 2019). Additionally, employing energy-efficient lighting devices, maximizing the utilization

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of unclaimed thermal energy, and improving its overall efficiency are key considerations (Mirkin *et al.*, 2013; Glebova, Glebov, and Sazhina, 2005). This has become especially important as part of the new climate agenda aimed at reducing the carbon footprint (Newell and Simms, 2020). In addition, the main energy-saving principles also include an economic feasibility assessment of using any energy-saving technologies and solutions (Glagoleva and Piskunov, 2021).

Oil refineries strive to enhance not only the energy efficiency level but also the depth of oil refining while maximizing the yield of gasoline, kerosene, and diesel fuel (Rossi *et al.*, 2020). Obviously, with an increase in the depth of oil refining, the number of technological processes and installations required to obtain motor fuels of the appropriate quality also increases, which requires significant capital investments. An increase in the depth of oil refining leads to an increase in the various energy resources consumption amount, such as high-pressure water vapor, electrical energy, as well as various types of fuel (mainly natural gas) (Mirkin *et al.*, 2014).

The production process of the oil refining marketable products includes three stages: primary oil processing (oil desalting and dehydration, its separation into fractions); secondary oil processing (fractions obtained at the primary processing stage take part in chemical reactions and are subject to subsequent fractionation); commodity production (there is a mixing of various fractions with additives in order to obtain commercial products with certain properties) (Akhmetov *et al.*, 2006).

At the primary processing stage, crude oil is introduced into raw tanks, where it undergoes a settling process to partially remove water and mechanical impurities. To facilitate oil dehydration and desalting, emulsifiers are added to the oil, which is then heated to temperatures ranging from 70 to 130 °C and subjected to an alternating electric field. These processes take place in electric dehydrators, where the pressure can reach up to 12 atm, and the alternating voltage value of 2 kV is applied (Bagdasarov, 2017; Podvintsev, 2011). Further, the crude oil is fed to the oil distillation column. In tube furnaces, for which the fuel is purchased natural gas or hydrocarbon gas and fuel oil produced at an oil refinery, oil is heated to a temperature of not more than 360 ° C and fed into a distillation column, into which water vapor enters (Wahid and Ahmad, 2016). The liquid in the lower column part enters the reboiler, where it is heated and partially vaporized, while the vapors move from bottom to top, passing through layers of liquid, which flows from top to bottom from one plate to another through overflow devices. Pressure and temperature decrease with column height. Straight-run fuel oil is removed from the bottom of the atmospheric distillation column cube, which is subjected to further processing in a vacuum distillation column. In some cases, to reduce the load on the main distillation column, a pre-topping oil column is installed. The raw material entering this column is heated in the heat exchangers system due to the hot flows of the main distillation column. Secondary oil processing includes many technological processes and installations, the composition of which may vary from refinery to refinery (Herzog, 2015). It should also be noted that the global trend in oil refining involves a steady increase in the depth of oil refining, which leads to a significant drop in the amount of bituminous raw materials, its shortage, and a decrease in the heavy oil fractions quality (Karpov *et al.*, 2021).

Oil refining processes require the consumption of various types of energy resources, and oil refining intermediate products often need to be cooled and condensed. In many oil refineries, secondary energy resources are reused. However, this approach is primarily applicable to hot streams with high-temperature potential, particularly side streams and bottoms from oil distillation columns. As for the rectification products in the gaseous state, the temperature of which is relatively low and does not exceed 150 °C, they are cooled and condensed in air and water coolers, for which energy is expended. A significant amount of waste heat energy from oil refineries is discharged into the environment instead of being reused profitably. In this regard, the possibility of reusing this heat, as well as the feasibility of such a solution, is being considered.

The article considers the process of cooling the raw material coming from the top of the column of the catalytic installation. During the study, a catalytic cracking distillation column with air coolers and water coolers was simulated to determine the emitted heat. It was assumed that the heat removed from the plant could be used to produce steam for technological needs, heat buildings, and generate electricity. After collecting the initial data on the selected installation, we simulated the processes of heating water with the heat of oil products in heat exchangers in order to determine what temperature the heated water would be and what its mass flow would be. Single-stage and two-stage water heating schemes were considered. We also simulated the Organic Rankine Cycle (ORC) with two configurations. In one case, we include the ORC scheme with a regenerative heater, while in the other case, the regenerative heater was not included in the scheme. These two models made it possible to determine how much electrical energy can be generated by utilizing the heat of oil products from the top of the catalytic cracking column.

The selection of the working fluid is not a primary focus in this study, as ORC equipment suppliers typically determine the appropriate working fluid themselves. This study presents new opportunities for resource conservation and environmental improvement through heat recovery from moderately hot streams, specifically in the context of oil refineries. If the feasibility of implementing the proposed solutions is confirmed, consideration of this problem can be very useful since the found methods of waste heat utilization can be applied to existing enterprises.

2. Methods

2.1. Initial data

This article discusses options for thermal energy utilization, which must be removed from the overhead of a catalytic cracking oil distillation column. The raw material obtained in the catalytic cracking process enters the distillation column. Heavy catalytic-cracking gas oil is removed from the column bottom, part of which is heated in a reboiler and returned back to the column. The overhead vapors of the column with a temperature of 125°C and a pressure of 0.1 MPa first enter the air coolers, where their temperature is reduced to 60°C, and then the vapor is fed to water coolers, where the temperature is reduced to 40°C. The resulting vapor-liquid mixture is separated in the separator into gas, condensate, and water. The separator pressure is 0.074 MPa, and the temperature is 40°C.

Since the purpose of the study is to find practical solutions, the initial data was provided by one of the operating oil refineries. The catalytic cracking unit was commissioned at JSC TANECO in 2021. It is capable of processing over 1 million tons of crude oil annually into a Euro 6 high-octane gasoline component. Also, the catalytic cracking unit products are light gas oil (raw material for EURO 6 diesel fuel) and liquefied hydrocarbon gases (propane-propylene and butane-butylene fractions) (Tatneft, 2021).

2.2. Determining the amount of heat removed

To determine the heat removal in air coolers and water coolers, an oil distillation column model was created using the Aspen HYSYS software package. The process of creating a mathematical model in the Aspen HYSYS software package includes the following main steps: specifying the chemicals involved in the simulated processes; the selection of thermodynamic mode, on the basis of which calculations will be performed; mathematical modeling, which includes the assignment of material, energy flows, technological installations; debugging the mathematical model and finding the optimal solution.

The Peng-Robinson equation-solving package was chosen for mathematical simulation. This equation is used to describe the phase transformations of oil and gas mixtures (Faizov, 2019). In the created mathematical model (Figure 1), the condenser simultaneously performs the functions of air coolers, water coolers and a separator.
To further refine the obtained results, separate models were created for the coolers and separator, independent of the oil distillation column.

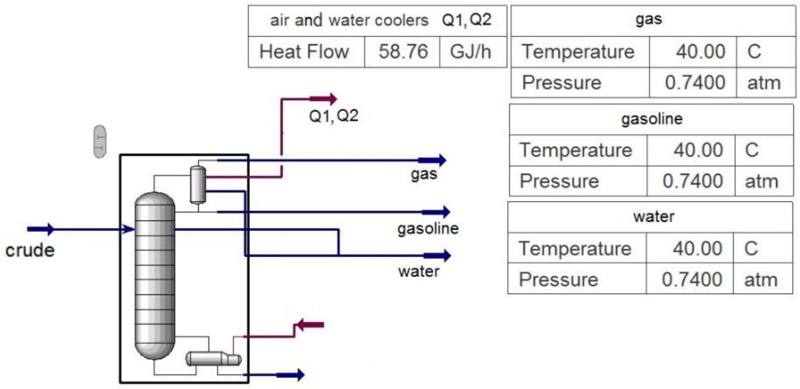

Figure 1 Column model with the condenser, which simultaneously performs the functions of air coolers, water coolers, and a separator.

2.2. Thermal energy utilization methods

2.2.1. Schemes with the use of heat exchangers for water heating

Oil refineries usually have their own boiler houses, in which network water is heated, and water vapor is obtained. Part of the steam is produced in waste heat boilers. In order to utilize waste heat and to increase the plant's performance, it is proposed to heat make-up water entering the steam boilers. This solution has already been implemented by Alfa Laval company at an oil refinery in the Canadian city of Sarnia, where Compabloc heat exchangers were installed as condensers in the oil distillation column of the catalytic cracking unit.

An alternative to this solution is the heating of water intended for a hot water supply system. Due to the large number of personnel working at the oil refinery, this enterprise has a large hot water demand. In accordance with Sanitary rules and norms, the water temperature for heat supply systems must be at least 60 °C and not more than 75°C (Sanitary Rules and Norms, 2021). The heat supply systems water at oil refineries is usually used not only for heating purposes, but it is also used for heating tanks with oil, fuel oil, and diesel fuel, and other needs (Mirkin *et al.*, 2014). In the variant under consideration, it is proposed to use a two-stage water heating scheme.

2.2.2. Technological schemes using the organic Rankine cycle

Currently, Rankine organic cycle installations are being implemented to generate electricity by utilizing low-grade heat extracted from various technological installations. The peculiarity of this cycle is that the working fluid in the turbine is not water vapor, as in conventional steam turbine plants, but an organic high-molecular substance, the boiling point of which is lower than the water boiling point. Therefore, the organic Rankine cycle can use low-potential energy sources. Rankine organic cycle installations can use heat in the temperature range from 90 to 400°C (Solomin, Daminov, and Kamalov, 2020; Riyanto and Martowibowo, 2015).

The working fluid is pumped to the evaporator, where it is vaporized and superheated. The pressurized steam is then fed into the turbine, where it expands, performing work. The exhaust steam is cooled and condensed, the condensate enters the pump, and the cycle is closed (Muslim *et al.*, 2019). A regenerative heat exchanger is often used in Rankine organic cycle installations. In this case, the steam transfers part of the heat to the cold working fluid and then condenses. Such a technological solution allows to increase in the heat recovery degree, as well as to increase the cycle efficiency (Leonov *et al.*, 2015).

Rankine organic cycle installations are used in various waste heat recoveries systems, such as geothermal power plants, exhaust gas heat recovery systems for gas turbine and gas piston installations, systems using the heat of hot process gases, and biomass power generation complexes. These installations are widespread in the world, but in the Russian Federation, there are only some power plants operating on the organic Rankine cycle, built in the middle of the 20th century and still operating (Paratunskaya GeoTPP and Mutnovskaya GeoTPP) (Dmitrenko and Kolpakov, 2021).

Freons (HFC-134a, HFC-245fa, OMTS), toluene, and Solkatherm (azeotropic solution) are the most widely used in the organic Rankine cycle. It is also possible to use cyclic hydrocarbons, for example, cyclopentane and cyclohexane, as well as butene, isobutene, etc. In scientific papers (Scagnolatto, Cabezas-Gómez, and Tibiriçá, 2021; Muslim *et al.*, 2019; Artemenko, 2014; Wang *et al.*, 2013; Saleh *et al.*, 2007), the issue of a working fluid selection, as well as the influence of various factors on the cycle efficiency, has been studied in detail.

The paper considers two options for organic Rankine cycle installations: with and without a regenerative heat exchanger. Cyclohexane was chosen as the working fluid.

3. Results and Discussion

3.1. The amount of heat removed from the catalytic cracking column overhead

As a result of a distillation column mathematical modeling of a catalytic cracking unit, the amount of heat removed by the column condenser was determined and amounted to 58.76 GJ/h. As a result of modeling, the processes occurring in the coolers and the separator, separately from the column (Figure 2), are consistent with the obtained value. Therefore, the model was created correctly, and the results obtained are suitable for further calculations.

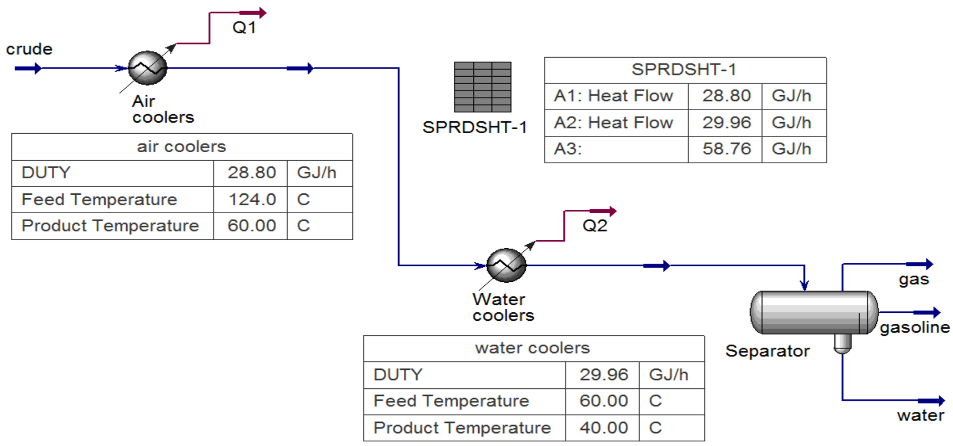

Figure 2 Scheme of cooling and condensation of the catalytic cracking column overhead vapors with their further separation

3.2. Mathematical modeling results of water heating schemes

With a thermal energy input of 58.76 GJ/h, it is feasible to heat 180.8 t/h of chemically treated water from 20°C to 95°C (Figure 3). The heated water, following deaeration, is then directed to steam boilers for the production of superheated steam.

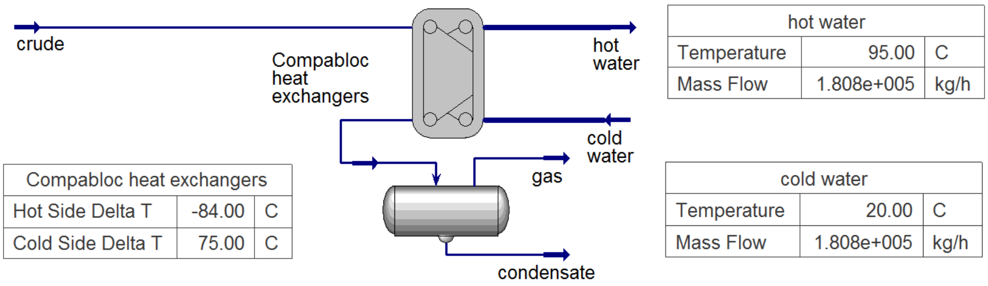

Figure 3 Model of chemically purified water heating using Compabloc heat exchangers

When we heat network water from 70 to 98°C and water for hot water supply from 5 to 68°C, we obtain mass flow rates of 138 and 160 t/h, respectively (Figure 4).

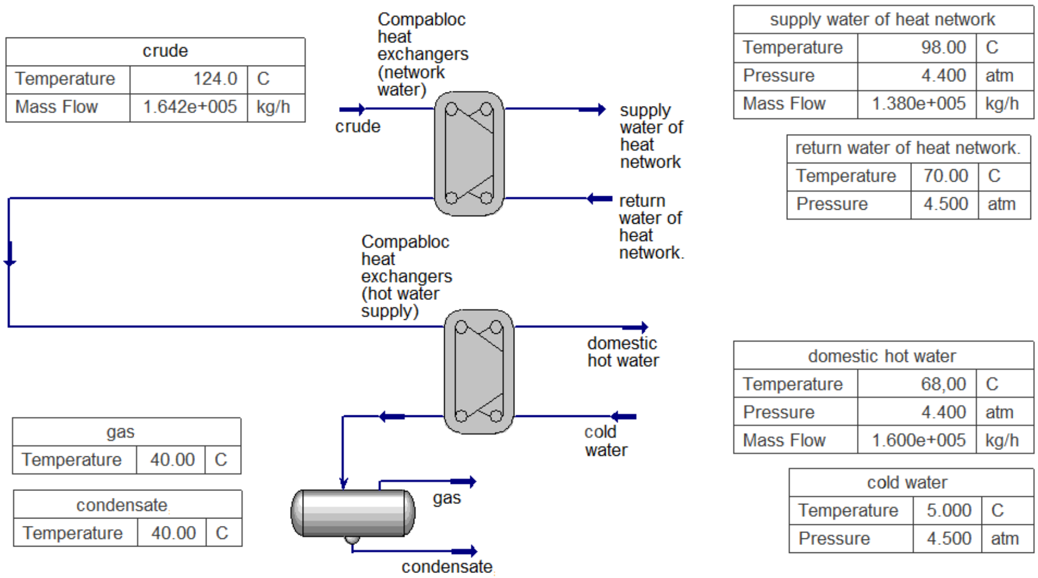

Figure 4 Water heating model of the hot water supply system and network water using Compabloc heat exchangers

It should be noted that this amount of heat in excess covers the needs of the refinery in hot water, so this solution is not optimal. The need for heating the network water is seasonal. Consequently, the amount of utilized heat will vary depending on the time of the year. During the warm period, the load on air coolers will increase significantly, which will lead to an increase in electricity consumption. We came to the conclusion that in this case, it is preferable to use waste heat for the further process of steam production rather than to heat water for district heating and hot water supply system.

3.3. Mathematical modeling results of technological schemes using the organic Rankine cycle

As noted above, the paper considers two options for low-grade thermal energy utilization using the organic Rankine cycle: with (Figure 4) and without the regenerative heat exchanger (Figure 5).

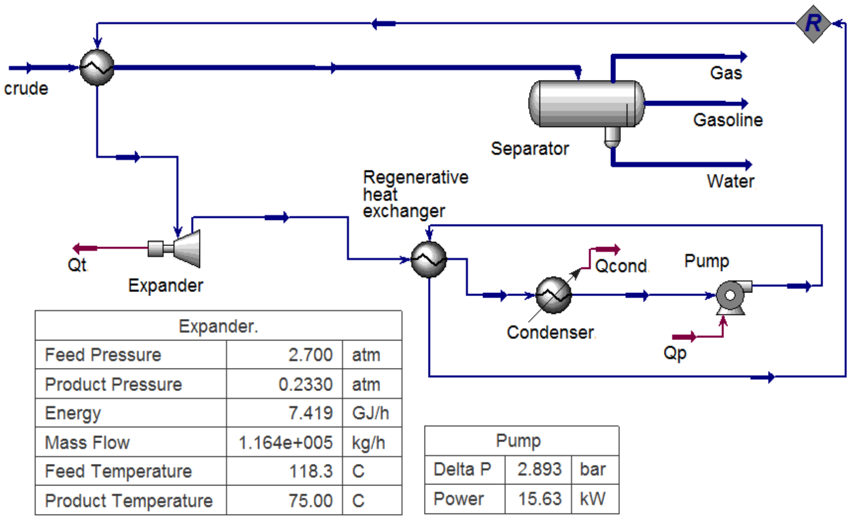

Figure 5 Organic Rankine cycle installation model with the regenerative heat exchanger

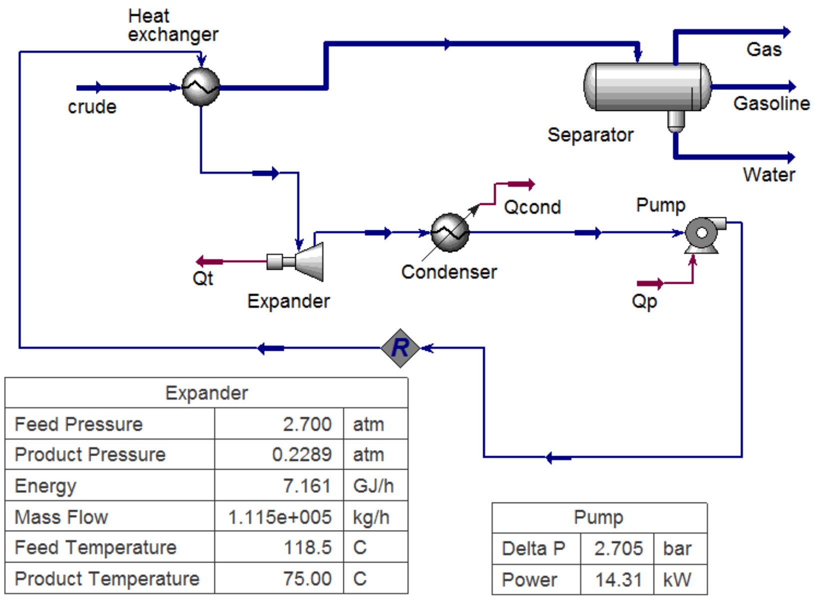

Figure 6 Organic Rankine cycle installation model without the regenerative heat exchanger

In some cases, the use of the regenerative heat exchanger can significantly increase the cycle thermal efficiency (Scagnolatto, Cabezas-Gómez, and Tibiriçá, 2021). The results obtained during mathematical modeling and further calculations are shown in Table 1.

Table 1 Rankine organic cycle installation performance characteristics

Experiment	Organic Rankine cycle installation with the regenerative heat exchanger	Organic Rankine cycle installation without the regenerative heat exchanger
Heat input, GJ/h	58.76	58.76
Heat input, kW	16322.22	16322.22
Turbine thermal capacity, GJ/h	7.42	7.16
Turbine thermal capacity, kW	2060.83	1989.17
Pump power, kW	15.63	14.31
Cycle thermal efficiency, %	12.53	12.10
Turbine electric capacity, kW	1682.34	1623.84

As shown in Table 1, we can produce more than 1.5 MW of electrical energy with an organic Rankine cycle installation. While this capacity may not cover all the energy needs of the oil refinery, it is sufficient for further evaluation of the technical solution's economic feasibility. The inclusion of a regenerative heat exchanger in the organic Rankine cycle installation allows for an increase in the generated electrical power. This reduces the heat load on the main heat exchangers and reduces the installation size (Murgia *et al.*, 2017). However, the results obtained indicate that in the case under consideration, the inclusion of a regenerator in the circuit did not lead to a significant increase in the cycle thermal efficiency 7.

4. Conclusions

The use of Compabloc heat exchangers makes it possible to utilize the maximum amount of heat removed from the catalytic cracking distillation column overhead. This technical solution will make it possible to obtain an additional reserve of steam capacity, which is important in terms of oil refinery performance increasing. It is not effective to use waste heat for heating water for district heating and hot water supply system. Moreover, the amount of heat in excess covers the needs of the oil refinery in hot water, so this solution is inappropriate. A significant disadvantage of organic Rankine cycle installation is the low efficiency. This means that part of the recovered heat is still released into the environment during the cooling of the working fluid in the condenser. However, this installation also has a number of significant advantages: the possibility of obtaining electricity from low-grade heat; the installation operates well at partial load, high degree of automation and ease of maintenance; long service life. At current price levels, installing Alfa Laval condensers will have a shorter payback period than the introduction of the organic Rankine cycle installation. At the same time, it should be noted that the organic Rankine cycle installation is controlled by the manufacturer, who maintains the unit, and, in this case, operating costs are taken into account. The heat exchange equipment is serviced by the plant's workers, whose wages are not taken into account in the calculation. The decision to build the Turboden organic Rankine cycle installation will reduce the number of employees, resulting in additional savings and a further decrease in the actual payback period. Despite all of the above, the final decision should be made based on the need for the oil refinery for a certain energy resource.

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