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The analysis of the energy index and the application of equivalent distillation productivity as criteria for identification of the energy efficiency of a petroleum refinery

Abstract: As a result of the development of industrial organic synthesis, the output of secondary processes in oil processing is becoming increasingly diverse. Production volume is a nodal indicator that is limited by the available production capacity, equipment configuration and the monetary equivalent of energy costs. In order to determine the technological potential and cost of produced petroleum products, it is necessary to create a complex that includes all stages of production. The most important criterion for evaluating the energy efficiency of an oil refinery is the relative energy consumption, which depends on its complexity. This criterion can be presented as a set of the different types of energy resources used in the course of production and applied to the total production. For this pur-

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pose, the energy resources invested in the given technology should be referred to a finished product or raw material. The peculiarity of oil refineries is that, due to the variety of oil derivatives, energy consumption, as a set of different installations, is much more appropriate to relate not to individual target products but to the amount of processed oil. In practice, all types of energy carriers must be converted to an equivalent value.

This paper provides an in-depth analysis of the energy costs of oil refineries. The collection of energy flows of different types and dimensions is the subject of the present study. Based on this, a method is presented that allows a comparison of the energy efficiency of refineries with different capacity and configuration of crude oil processing stages based on the energy index and the equivalent distillation performance.

Keywords: energy index, energy costs, energy efficiency, petroleum refinery

Introduction

In oil refineries, depending on the organization of the technological process, thermal engineering and power systems of different types are used. The classic scheme is through the use of water vapor as a heat carrier brought to the individual productions through a heat-transfer network (Kostov et al. 2022). In order to perform an energy-efficiency analysis of energy consumption (de Lima and Schaeffer 2011; Łebkowski et al. 2015; Wu et al. 2017; Ghadim and Faridzad 2021), it is important to introduce a single criterion with which to evaluate energy consumption. The introduction of such a criterion should represent the total used energy resources related to a finished product or raw material. A special feature with regard to oil refineries is that due to the variety of oil derivatives, with regard to the energy consumption of the plant as a set of different installations, it is much more appropriate to refer not to the individual target products, but to the processed raw material (oil) measured in metric tons or barrels. In practice, all types of energy carriers, such as different types of fuels, heat supplied by steam and hot water, electrical energy of all voltage levels, desalinated and circulating water, technical air and gases creating an inert environment and others, must be translated to an equivalent value – tons of oil equivalent (toe) or energy (GJ or MWh).

The collection of energy flows of different types and dimensions is a labor-intensive task, but in essence, its realization is not a problem. Formulated in this way, the concept of energy consumption has a clear physical meaning, it is easily defined and enables the assessment of the dynamics of change and traceability over time. A major drawback of the method is that it does not allow comparability with similar oil refineries. The reason for this is that although they are similar, the refineries have different productivity, technological configuration and technical levels of equipment. On the other hand, the monetary equivalent of energy costs occupies a primary share (excluding oil purchase costs) in the maintenance of the enterprise and are essentially the most important factor in market competition.

Attempts to compare operating oil refineries with different productivity and technology have been made in research (Gary et al. 2007; Riazi et al. 2013; Kaiser 2017; Herce et al. 2022). These studies are based on the work of Nelson (1976a), who established the proportional relationship between the technological complexity of oil-refining processes and the amount of capital investment required for their implementation. For example, if an atmospheric distillation of a standard crude oil unit (SCU) has a complexity factor of SCU = 1.0, a pseudo fluidized-bed catalytic cracking (FCC) plant should have a complexity factor of FCC = 8.2. This is because the capital investment per ton of feedstock processed at the installation FCC plant is 8.2 times greater. The set of technological installations, depending on the specific configuration of each oil refinery, forms a characteristic "complex energy index" subsequently named after the discoverer. Nelson's index is an objective criterion for evaluating the technological complexity of refineries, and in Nelson (1977) the author rightly suggests using it as a correlation factor in their comparison. The main conclusion is that technologically more complex oil refineries, i.e. those with a larger index, generally have higher energy costs. At the time he conducted his research (Nelson 1976a) and published the results, analysis of the data showed a similar correlation of the US refineries studied. However, it should be noted that, with few exceptions, all refineries at the time used low temperature processes and were constructed of standard construction materials. The use of the original technological complexity coefficients in their original form is inapplicable nowadays because three main factors are not taken into account:

- the costs for the oil terminals, the storage of the raw material and the distribution of the finished product;
- the dynamics in the development of the industry, the emergence of new construction materials, new technical concepts and new technologies;
- the sharp and significant change in the structure of operating costs in all categories.

For the last 20 years, for example, the price of energy carriers has increased several times, while the costs of labor, chemical reagents, spare parts, etc., despite having increased in absolute terms, already occupy a much smaller share in the total amount of maintenance. This is why the coefficients for technological complexity have undergone significant development and today significantly differ from the original values (Zhang et al. 2001; Bandyopadhyay et al. 2019; Dalei and Joshi 2020; Atris 2020).

1. Materials and methods

Solomon Associates' trusted benchmarking methodology was first implemented in the US in 1980. It is still used for commercial purposes, but it takes as its axiom some basic notions of performance evaluation, such as:

- larger oil refineries have undeniable advantages over smaller ones;
- newer refineries are always more efficient;

- technologically more complex refineries are more profitable;
- the most efficiently operating refineries are located near deep-sea ports.

The company's very first report has cast doubt on some of these widely held beliefs. For example, some relatively small oil refineries turned out to be quite efficient, and vice versa – the indicators of some large and new plants turned out to be below average. Currently, the company Solomon Associates, based on comparative analyses of oil refineries around the world, has accumulated an extremely rich database of more than 500 refineries. Systematizing and comparing these refineries creates a unique opportunity to validate the method and verify the results. The analysis is performed for the relevant geographical area, and the oil refineries according to the relevant indicators are grouped into four quartiles. The first quartile includes the best oil refineries.

To evaluate the energy efficiency of an oil refinery, the company Solomon Associates (SA) introduces the correlation parameter "Solomon Energy Intensity Index" or "Solomon EII" or "EII". This benchmark is an oil refinery energy efficiency metric that compares the actual energy consumption of a refinery with the "standard" energy consumption of a refinery of similar size and configuration. The formula for determining EII looks like this:

$$EII = \frac{AECOR}{day \cdot (ES \cdot UEDP + HC + ESWD)} \cdot 100 \tag{1}$$

where:

AECOR – actual energy consumption of an oil refinery,
ES – energy standard,
UEDP – usable equivalent distillation performance,
HC – heat content,
ECWD – energy consumption for water desalination.

The actual energy consumption of the refinery is:

$$AECOR = RTE + HEE \tag{2}$$

where:

RTE – the required thermal energy,
HEE – heat equivalent of electricity.

Before analyzing Equation 1, assumptions are introduced that the required thermal energy is a sum of the heat obtained from the combustion of the fuels and the heat absorbed by all other heat carriers, and that the thermal equivalent of the electricity is assumed to be 9090 Btu per 1 kW. Essentially, the denominator of Equation 1 represents the standard energy consumption of the installation. Obviously, when the actual consumption matches the standard, the index $EII = 100$. The standard energy consumption consists of several multipliers. The first and most important of these is usable equivalent distillation productivity (UEDP). The determination of UEDP takes place in several stages:

1. The so-called stream-day (SD) throughput of the refinery is determined. This is the nominal performance for a calendar day at 100% utilization during the year, at the maximum possible sustainable load, without peak overloads. Atmospheric distillation is the first technological process along the course of the raw material, which is why the stream-day productivity of the refinery and the atmospheric distillation plant match.

2. The productivity of each subsequent installation in the technological chain decreases with the extraction of the target products. This is determined by multiplying the stream day productivity of the refinery by a factor taking into account the percentage share of the specific installation in the total oil processing. The term “installation” is collective – it means both purely technological units and all auxiliary and energy systems related to the production of thermal and electrical energy.

3. The equivalent distillation productivity (EDP) is determined by multiplying the productivity per calendar day for each installation by the relevant technological complexity factor (K_T) – (Table 1, Column 3).

4. The usable equivalent daily productivity (UEDP) is obtained by multiplying the EDP with a proportionality factor (K_P) taking into account the actual working time of the particular installation for the studied period and a multiplicity factor (K_M). The latter coefficient is entered if two or more installations with the same purpose are available in the configuration of the oil refinery.

Table 1 presents the technological complexity factor (K_T) and the standard energy consumption of some typical technological installations of an oil refinery.

Based on the analysis conducted for UEDP, it can be stated that:

$$UEDP = \Sigma\left[\left(SD \cdot \left(\frac{\%SD}{100}\right) \cdot K_T \cdot K_P\right) \cdot K_M\right] \tag{3}$$

where:

SD – stream day,
K_T – technological complexity factor,
K_P – proportionality factor,
K_M – multiplication factor.

To determine the UEDP for the entire refinery, it is necessary to determine the equivalent daily productivity of each of the external facilities for the refinery – oil terminals, commodity – raw materials bases, state reserve bases, etc.:

$$EDPEO = \Sigma\left(PEO \cdot K_C\right) \tag{4}$$

where:

PEO – permeability of external objects,
K_C – configuration coefficient.

The configuration coefficient (K_C) is analogous in a physical sense to the technological complexity coefficient (K_T) and its purpose is to unify external objects by type and throughput (Table 2).

TABLE 1. Technological complexity factor (K_T)

TABELA 1. Współczynnik złożoności technologicznej (K_T)

Process Type	Process Type ID	K_T	Energy standard [BTU/barrel of oil]
Atmospheric crude distillation			
Standard crude unit	SCU	1.0	3 + 1.23×°API
Mild crude unit	MCU	0.8	3 + 0.94×°API
Vacuum distillation			
Standard vacuum colimm	VAC	1.0	15 + 2.3×°API
Vacuum fractionating columm	VFR	1.2	25 + 2.3×°API
Mild vacuum fractionating	MVU	0.8	12 + 1.1×°API
Heavvy feed vacuum unit	HFV	1.0	15 + 1.85×°API
Visbreaking			
Vacuum bottoms feed	VBF, VBFS	3.2	140
Atmosspheric resid	VAR, VARS	3.2	140
Thermal cracking		3.8	220
Coking			
Delayed coking	DC	7.5	180
Fluid coking	FC	7.5	400
Flexicoking	FX	11.0	575
Catalytic cracking			
Fluid catalytic cracking	FCC	8.2	70 +[40 × (coke, % raw material)]
Mild residual catalytic cracking	MRCC	9.1	70 +[40 × (coke, % raw material)]
Residual catalytic cracking	RCC	10.0	70 +[40 × (coke, % raw material)]
Catalytic reforming			
Cyclic	RCY	3.5	[3.65×(C5 +RONC)]-120
Continuous regeneration	RCR	3.6	[3.65×(C5 +RONC)]-133

Note: 1. Density in degrees API for each installation.
2. RONC octane number according to the motor method.

Represented in this way for the entire oil refinery, the usable equivalent distillation productivity will be equal to the sum of the daily productivity of the process plants and external sites:

$$UEDP_{\text{refinery}} = \sum UEDP_{\text{installation}} + EDPEO \qquad (5)$$

Table 2. Configuration coefficient (K_C)

Tabela 2. Współczynnik konfiguracji (K_C)

Type of transportation	Delivery of petrol	Expedition of the product
Railway tanks	0.50	0.50
Tanker trucks	0.40	0.40
Tanker terminal	0.10	0.21
Offshore buoy	0.10	0.10
Barge terminal	0.10	0.15
Pipeline	0.00	0.00

Since UEDP has no real physical meaning, it can be used as a correlation parameter for the unification, evaluation and comparison of oil refineries with different configurations.

When determining the energy index (EII), it is necessary to take into account another important parameter – the energy standard (ES).

For the requirements of oil refineries, energy standards have been developed for all possible combinations of technological processes for the production of fuels and oils. For the purposes of this study, a sampling of the energy standards of some of them are presented in Table 1. Once determined, these standards are not of a constant value and need to be periodically updated in connection with the implementation of new construction materials and the development of technologies. The heat content of the crude oil (200°F – 93.3°C) and a proportional part of the energy costs necessary for the operation of the general plant economy located outside the limits of the specific production must be added to the energy consumption of the installations.

2. Discussion

The object of the research is the oil refinery located in the city of Burgas, in the Republic of Bulgaria. It is the largest oil refinery in the southeast of Europe and the largest industrial enterprise in Bulgaria. It was put into operation in 1963 and is a classic type of refinery with a complex Nelson index of 8.9. The principle technological scheme is presented in Figure 1.

The research aims to determine and compare the relative energy consumption and the EII energy index, and then to follow and analyse the trend and dynamics of their changes over an eight-year period. Achieving the set goal should be considered as a stage in the implementation of a system for monitoring key indicators of energy efficiency, to be integrated with appropriate software in the management information system (SAP R3) of the refinery. The ultimate goal is the creation of conditions for an objective analysis of the achieved results and the determination of competitive advantages and restraining factors in the implementation of the energy policy and the management of the refinery as a whole.

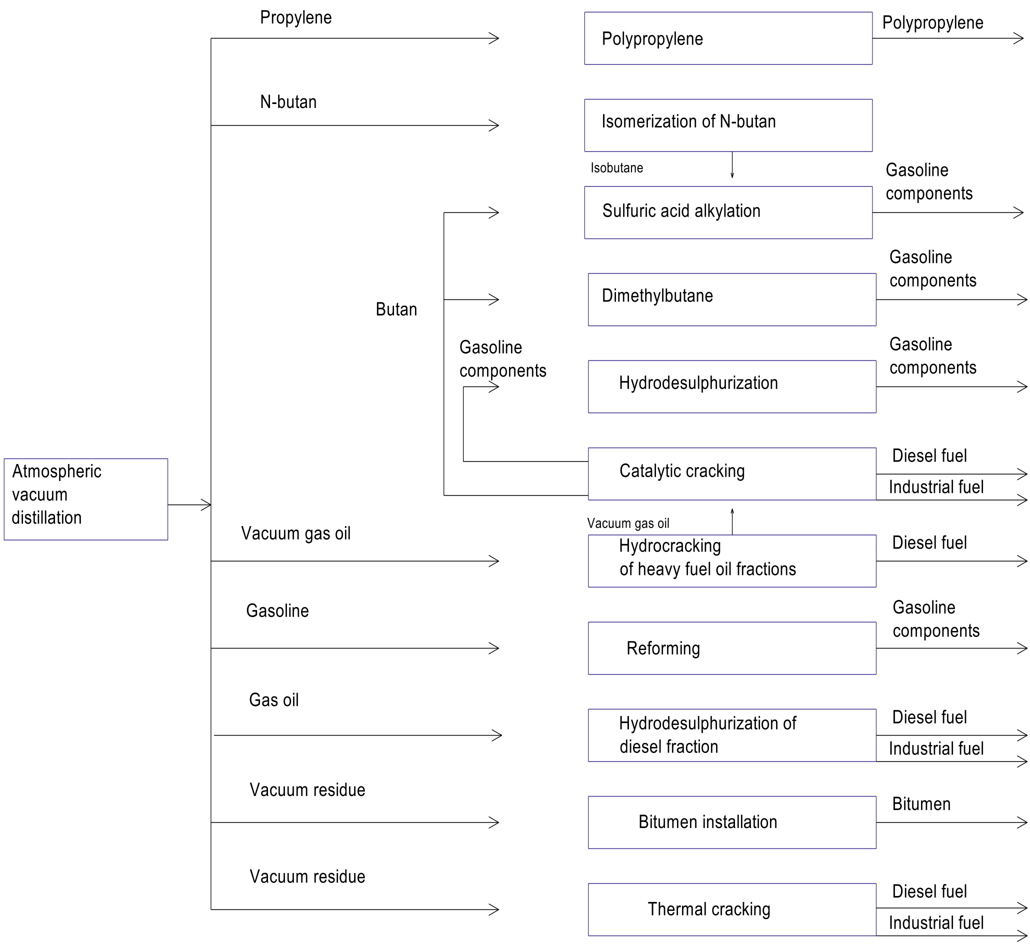

Fig. 1. Block diagram of the refinery

Rys. 1. Schemat blokowy rafinerii

The main information required for the study is contained in the monthly and summarized annual reports of the technological installations of the refinery. It concerns an energy analysis covering a long period so that the average values of the energy indicators within a calendar month are sufficiently representative to eliminate the influence of the inevitable fluctuations in the instantaneous values determined by transitional and technological regimes. The determination of the relative energy expenditure is performed on an annual basis, and every two years in the case of the complex energy index (*EII*). The result is shown in Figure 2.

According to the set goal, the change in the energy index EII is compared with the change in the energy intensity defined as the consumption of conditional fuel referred to the processed oil (toe). On the chart, based on data provided by the SA consultant, the first and fourth quartile limits determined by a study of eighty-nine refineries from eastern and southern Europe are shown

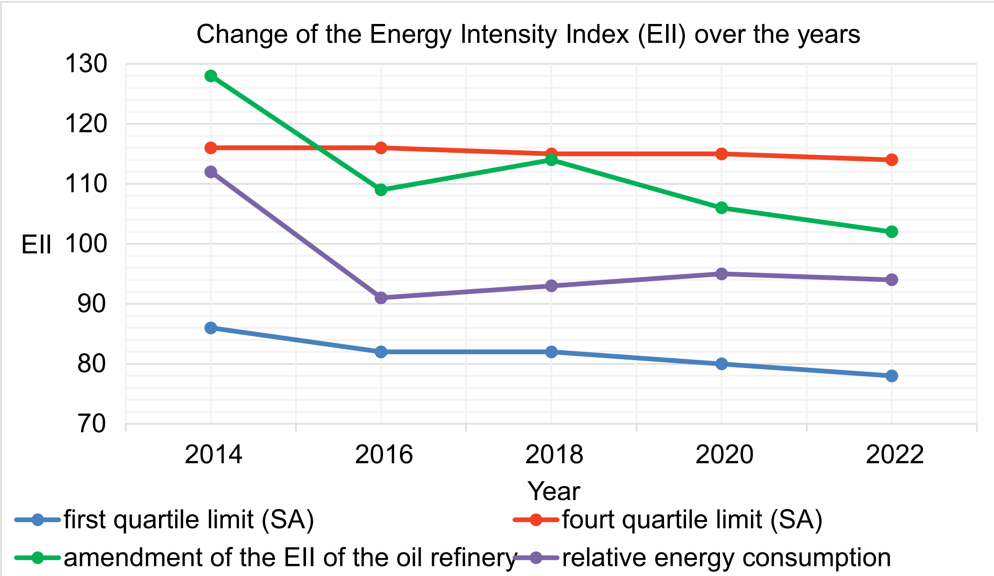

Fig. 2. Change in the *EII* energy index and relative energy consumption

Rys. 2. Zmiana wskaźnika energetycznego *EII* i względne zużycie energii

for reference. The change of both indicators is in the direction of improvement with a positive downward trend, but there are some peculiarities.

The *EII* amendment gives an indication that the refinery is implementing reforms in the management of energy flows and implementing measures to reduce energy consumption at a faster pace than competitors. If all refineries had the same progress and moved in a pack, the *EII* index would be unchanged. The first period (2014–2016), when the decrease was 14.3% compared to the initial value, is particularly indicative. The explanation is that for two years, organisational and technical energy-saving measures were successfully implemented with a short implementation period and a significant effect. Relative energy consumption also decreased by 11.2%. In the next two-year period, the energy index grew and reached the limit of the fourth quartile. The reason is rooted in two serious accidents that put major installations out of order for a long time at the beginning of 2017 and the middle of 2018. The relative energy consumption changed insignificantly because emergency stops have no direct relation to its value.

The 2018–2020 period is characterized by the entry into regular operation of investment sites with a higher coefficient of technological complexity aimed at improving the assortment and quality of the finished product. Logically, an increase in IEDP and standard energy consumption follows, and together with them, a decrease in the *EII* index. At the same time, the relative energy consumption increases because the volume of oil processed does not change, but the actual energy consumption increases. This trend continued in the next two-year period. The energy index decreased by 7.5%, while the relative energy intensity remained unchanged. Research for 2022 determines *EII* = 98 < 100. The refinery approached the limits of the third quartile, and for the first time, the actual energy consumption is below the values of the standard for the specific technological configuration.

Conclusion

The conducted analysis shows indisputable progress regarding the energy policy and efficiency of the considered refinery, but the EII energy index still positions it at the border between the third and fourth quartile. To some extent, this is due to the fact that the energy of thermal energy flows is not taken into account. The presence of secondary energy carriers, such as low-caloric gases and low-pressure steam, represent sources of energy, but their simple summation as a heat equivalent is incorrect. Despite the stated critical remarks, the proposed method has its merits and does not call into question the fundamental regularities on which it is based. The possibility to estimate the energy intensity of the refinery by means of an energy index based on energy standards and the equivalent distillation capacity is applicable to the comparison of oil refineries that have different levels productivity and different configurations.

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Analiza wskaźnika energetycznego i zastosowanie ekwiwalentnej wydajności destylacji jako kryteriów identyfikacji efektywności energetycznej rafinerii ropy naftowej

Streszczenie

W wyniku rozwoju przemysłowej syntezy organicznej wydajność procesów wtórnych w przetwórstwie ropy naftowej staje się coraz bardziej zróżnicowana. Wielkość produkcji to wskaźnik węzłowy, który jest ograniczony dostępnymi zdolnościami produkcyjnymi, konfiguracją urządzeń oraz ekwiwalentem pieniężnym kosztów energii. W celu określenia potencjału technologicznego i kosztu wytwarzanych produktów naftowych konieczne jest stworzenie kompleksu obejmującego wszystkie etapy produkcji. Najważniejszym kryterium oceny efektywności energetycznej rafinerii ropy naftowej jest względne zużycie energii, które zależy od jej złożoności. Kryterium to można przedstawić jako zestaw różnych rodzajów zasobów energetycznych wykorzystywanych w trakcie produkcji i stosowanych w całej produkcji. W tym celu zasoby energii zainwestowane w daną technologię należy odnieść do gotowego produktu lub surowca. Specyfika rafinerii ropy naftowej polega na tym, że ze względu na różnorodność produktów ropopochodnych energochłonność, jako zespół różnych instalacji, znacznie bardziej adekwatnie odnosi się nie do poszczególnych produktów docelowych, ale do ilości przerobionej ropy. W praktyce wszystkie rodzaje nośników energii muszą być przeliczane na wartości równoważne. Artykuł zawiera dogłębną analizę kosztów energii rafinerii ropy naftowej. Przedmiotem niniejszego opracowania jest zbiór przepływów energii różnych typów i wymiarów. Na tej podstawie przedstawiono metodę pozwalającą porównać efektywność energetyczną rafinerii o różnej wydajności i konfiguracji etapów przerobu ropy naftowej na podstawie wskaźnika energetycznego i ekwiwalentnej wydajności destylacji.

Słowa kluczowe: indeks energetyczny, koszty energii, efektywność energetyczna, rafineria ropy naftowej