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Performance of the Dutch Energy Sector based on energy, exergy and Extended Exergy Accounting

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Abstract

The performance of the Dutch Energy Sector is analyzed using the Standard Exergy Analysis as well as Extended Exergy Accounting (EEA) method. Performance indicators based on energy, exergy and cumulative exergy consumption (CExC) are evaluated for three subsectors: exploitation, transformation, and distribution of energy. It is shown that performance indicators based on CExC are much lower than those based on energy and exergy concepts. The EEA method is applied for analysis of four branches: cokeries and refineries, refineries, central electricity production, and distribution and decentral electricity production. The EEA method originally proposed by Sciubba is modified by evaluating the cost-to-exergy conversion factor from the monetary value and CExC of the feedstock. It was found that the monetary equivalent of extended exergy is higher than the respective product sales. Finally, it is shown that performance indicators of selected energy branches based on extended exergy are much lower than those based on the CExC.
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Keywords: Exergy analysis; Energy management; Energy policy; Environmental impact

1. Introduction

In the last three decades energy efficiency is considered as one of the major components of economic policies in many countries. The efficient use of energy has also now an important place in the public debate. It is generally believed that improvement in performance at different stages of energy systems is a very effective mean to decrease global energy consumption. The importance of energy efficiency is also linked to environmental problems, such as global warming and atmospheric pollution.

One of the difficulties with measuring energy efficiency is the lack of consensus on the evaluation of performance of all stages of energy systems, ranging from primary, secondary to final energy use. Energy efficiency is a rather general term and in practice various energy performance indicators are used, usually grounded in thermodynamics or economics. The thermodynamic indicators can measure either the first-law

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Nomenclature

CEE	capital equivalent exergy (PJ)
CExC	cumulative exergy consumption (PJ)
CS_t	capital stock in year t (mln €)
EE	extended exergy (PJ)
ERE	environmental remediation exergy (PJ)
Ex_p	product exergy (PJ)
FE	feedstock exergy (PJ)
I_{ST}	short-term investment (mln €)
K_{cap}	specific capital conversion factor (mln €/PJ)
LEE	labor equivalent exergy (PJ)
LEE_{SA}	labor equivalent exergy due to social account (PJ)
LEE_{Skill}	labor equivalent exergy due to skill (PJ)
LEE_w	man-power equivalent exergy (PJ)
PS	product sales (mln €)
η	efficiency, dimensionless

Superscripts

€	monetary value

Subscripts

EN	energy
EX	exergy

efficiency or the second-law exergetic efficiency. The economic indicators measure the performance in terms of economic values, such as energy prices.

The main shortcoming of commonly used performance indicators of energy efficiency is their 'one-dimensional' character what means a restriction to only one performance aspect. Traditionally, exergy analysis is restricted only to thermodynamics, whereas economical and environmental aspects are not involved. Energy efficiency indicators that are 'multi-dimensional' have to be demonstrated in order to become the sustainability tools in engineering practice and energy policy. A significant problem with complex indicators is that they have to be based on weight factors needed to compare different sustainability aspects and represent the final evaluation result in the same units.

Thermodynamic indicators of process performance based on the second law are nowadays commonly accepted as the most natural way to measure the performance of different processes, ranging from energy technology, chemical engineering, transportation, agriculture, etc. Exergy-based indicators, originally used as an 'one-dimensional' thermodynamic indicator, have been coupled with Life Cycle analyzes concepts to become a 'two-dimensional' indicator, such as the cumulative exergy consumption (CExC) proposed by Szargut [1]. An important development to couple exergy and economy was the formulation of 'exergoeconomy' where efficiencies are calculated via an exergy analysis and 'non-energetic expenditures' (financial, labor and environmental remediation costs) [2,3]. Similarly, the coupling between exergy analysis and ecology has been presented by Rivero [4], and Rivero and Anaya [5].

Recently, Extended Exergy Accounting (EEA) has been proposed by Sciubba [6,7] as an extension of standard exergy analysis to include also economic and environmental issues. The advantage of performance indicators based on the EEA is that they can be used as exergetic as well as monetary metrics for all stages of energy systems. The application of EEA has been demonstrated for a single process of ethanol production [8] and recently, the analysis of the Norwegian society 2000 has been made by Ertesvåg [9] based on energy, exergy and extended exergy.

The purpose of this paper is to demonstrate how the EEA can be applied at the sector level, namely to the Dutch Energy Sector. We report here the results of analysis of this sector using the standard exergy analysis in terms of computing the energy, exergy, and CExC values of the input and output streams of the sector. Further, the procedure for evaluation of EEA is explained and finally the efficiency indicators based on EEA are calculated.

2. Dutch Energy Sector: standard exergy analysis

2.1. The Dutch Energy Sector

A methodological reason to study the energy sector is that flows into and from this sector are relatively homogeneous with a relatively short economic life. Moreover, the volumes of natural resources processed within the sector are large, thereby directly being relevant to environmental issues such as natural resource scarcity and atmospheric pollution. Furthermore, the energy consumption of the energy sector makes up for almost 20% of the national energy consumption in 1996.

The analysis of the Dutch Energy Sector 1996 is based on mass-flow data published by the Statistics Netherlands [10]. The data allows for a breakdown into 8 branches, and 27 mass flows of energy carriers.

The 8 branches are classified in three subsectors, as exploitation, transformation, or distribution of energy, as indicated below:

- Exploitation
- Transformation
  - cokeries
  - refineries
  - central electricity and heat production
  - decentral electricity and heat production
  - refuse incinerators
- Distribution
  - solid fuel trade
  - oil product trade
  - distribution of water, gas, electricity and heat.

The branch of refuse incinerators is not included in the present analysis as no fossil energy carriers are involved. For each of the remaining seven branches, the 27 mass-flow accounts are grouped into three main categories based on the primary resource:

- *Hard coal (products)*: Hard coal and lignite, coke, coke oven gas, blast furnace gas, other hard coal derivates.
- *Crude oil (products)*: Crude oil, natural gas condensate, other crude oil raw materials, refinery gas, chemical waste gas, LPG/butane/propane, naphtas, oil aromatics, aviation gasoline, jet-fuel (kerosene basis), motor gasoline, other light oils, kerosene, gas-, diesel-, fuel oil <15 cST, gas-, diesel-, fuel oil $15>$cST, lubricants and greases, bitumen, other oil products.
- *Other energy carriers*: Natural gas, electricity, steam and hot water, organic waste gas.

On a national level, the Dutch energy balance is dominated by trade (see Table 1). The data presented in this table shows the main components of the energy balance, whereas some important constituents of these components are indicated in italics. The total amounts of trade (import and export) exceed the domestic exploitation and consumption. Both import and export products are mainly crude oil and oil products.

The Dutch exploitation sector (see Table 2) is dominated by natural gas. Large reserves were discovered in the North of the Netherlands in 1959 (Slochteren, Groningen). In 1996, natural gas (2891 PJ) contributed for

Table 1
Energy balance 1996 for the Netherlands

Input (PJ)			Output (PJ)		
Exploitation		3119	Domestic consumption		3076
Natural gas	2891		Crude oil	2441	
Import		6506	Natural gas	1598	
Crude oil	4227		Crude oil products[a]	−1737	
Crude oil products	1356		Export		5960
Bunker		−601	Crude oil	1898	
Stock mutation		12	Crude oil products	2485	
			Natural gas	1464	
Total		9036	Total		9036

[a]The negative output in this case means production exceeds consumption.

Table 2
Energy balance for the exploitation sector

Input (PJ)			Output (PJ)		
Exploitation		3029	Consumption		34
Natural gas	2891		Natural gas	34	
Feedstock		172	Production		3169
Natural gas	171		Natural gas	3029	
Stock mutation		1			
Total		3202	Total		3202

90% to the energy balance of the exploitation sector. Only half is for domestic use (1598 PJ), whereas the other half is exported to surrounding countries. The natural gas is mainly exploited by the Nederlandse Aardolie Maatschappij (NAM) that also exploits small amounts of crude oil. The published statistics do not include recycle flows such as biomass waste and other refuse. Within the domestic use, natural gas is mainly a feedstock to the energy sector that deals with the distribution of water, gas, electricity and heat (33%); 9% is used for central electricity production. Outside the energy sector, industries and households both consume 16% of the natural gas produced.

The main feedstock to the refineries, a branch within the transformation sector (see Table 3), is crude oil and crude oil products. Refineries process over 80% of the incoming crude oil, producing products ranging from fuels to chemical input for bulk chemicals (ethylene, propylene). These products make up for almost three quarters of the total crude oil production of the transformation sector. Much smaller is the cokery branch, which is concentrated in one organization (Hoogovens). The hard coal products make up for only 2% of the total production of the transformation sector. Central power plants use natural gas as main feedstock. Decentral electricity and heat production involves mainly plants where electricity is a by-product of heat production.

The distribution sector has large throughput. The three branches identified (solid fuel trade, oil product trade, and electricity, heat, natural gas and hot water distribution) are represented in Table 4. Large amounts of crude oil and oil products are imported, processed or directly exported over the Rhine to Germany's Ruhr area. Solid fuel trade makes up for only small part. The last branch is mainly made up by central power plants.

2.2. Analysis of the Dutch Energy Sector based on energy, exergy and CExC indicators

This section presents three efficiency indicators based on energy, exergy, and CExC, respectively. Energy, exergy and CExC flows for all branches of the Dutch Energy Sector are computed, based on the annual

Table 3
Energy balance for the transformation sector

Input (PJ)			Output (PJ)		
Exploitation		75	Consumption		532
Steam/hot water	75		Production		5116
Feedstock		5568	Crude oil	1069	
Crude oil	3500		Crude oil products	3589	
Crude oil products	1034		Hard coal products	104	
Hard coal	367				
Natural gas	352				
Stock mutation		5			
Total		5647	Total		5647

Table 4
Energy balance for the distribution sector

Input (PJ)			Output (PJ)		
Exploitation		3	Consumption		30
Feedstock		5612	Production		5595
Crude oil	1431		Crude oil	1446	
Crude oil products	2549		Crude oil products	2538	
Natural gas	881		Natural gas	851	
Stock mutation		10			
Total		5625	Total		5625

mass-flow data of the above-mentioned 27 substance accounts. To this end the mass-flow data of every account are multiplied by: (a) its net-calorific value, (b) its specific exergy value, and (c) a value representing its CExC, respectively:

(a) The average net-calorific values were available from Statistics Netherlands [10].
(b) The specific (chemical) exergy of nine substances have been taken from the database in the software program EcoChem by Cornelissen et al. [11]: hard coal, coke, crude oil, LPG, gasoline, petroleum, diesel, heavy oil, and steam. For the remaining accounts the specific (chemical) exergy values are calculated using correlations for technical fuels by Szargut et al. [12].
(c) CExC values are taken from the life-cycle information in the software program EcoChem based on cost factors being the ratio of CExC to (chemical) exergy of a feedstock [11].

Table 5 presents the results of energy, exergy and CExC flows for the three sub sectors of the Dutch Energy Sector, which are calculated as explained above. Based on the three different valuations, three efficiency indicators (η), defined by the ratio of production (output) and input are shown in Table 6.

For the entire sector, the energy η_{EN} and exergy η_{EX} based indicators are almost the same. This is due to the fact that the net-calorific values and specific exergy values for all present substances are quite the same. The CExC-indicator η_{CExC} shows significant lower values, reflecting a 'cradle-to gate' history of a feedstock and involving a partial life cycle analysis. Comparing the different subsectors, it is noted that where the activity does not involve transformation of the feedstock, the η_{EN} and η_{EX} indicators approach unity. The transformation subsector shows lower indicators, which is explained by a lower specific exergy value of the product compared to the feedstock. A further breakdown into branches shows a higher performance of refineries ($\eta_{EX} = 0.96$) compared to central electricity production ($\eta_{EX} = 0.42$).

The energy and exergy indicators presented in Table 6 agree with the efficiency data for OECD countries in 1990 published by Nakićenović et al. [13] where the whole energy chain was divided into primary, secondary, final, useful energy, and energy services. The exploitation and transportation subsectors correspond to

Table 5
Energy and exergy flows for subsectors of the Dutch Energy Sector

Sub sector	Input (PJ)			Production (PJ)	
	Energy	Exergy	CExC	Energy	Exergy
Exploitation	3202	3337	3372	3169	3303
Transformation	5647	5973	6217	5116	5407
Distribution	5625	5942	6649	5595	5904
Dutch energy sector	14,474	15,252	16,238	13,879	14,615

Table 6
Efficiencies for subsectors of the Dutch Energy Sector

Sub sector	η_{EN}	η_{EX}	η_{CExC}
Exploitation	0.99	0.99	0.98
Transformation	0.91	0.90	0.87
Distribution	0.99	0.98	0.89
Dutch Energy Sector	0.96	0.96	0.90

conversion of the primary to secondary energy whereas the distribution subsector corresponds to conversion of the secondary to final energy. The efficiencies of these conversion steps are relatively high whereas efficiencies related to the useful energy and energy services, which are not examined in this paper, are much lower.

3. EEA of the Dutch Energy Sector

According to Sciubba [7] the Extended Exergy contains the following parts: feedstock exergy (FE) being the CExC of feedstock, capital equivalent exergy (CEE), labor equivalent exergy (LEE), and environmental remediation exergy (ERE). The extension of the classical exergy concept by capital and labor equivalents had been motivated by Sciubba by Neo-Classical Economics (NCE) where capital and labor are identified as production factors that contribute to performance. The Extended Exergy can be calculated from its constituent's components:

$$EE = FE + CEE + LEE + ERE. \tag{1}$$

The FE component can be computed based on the mass-flow data. In order to address the economical (CEE and LEE) and environmental (ERE) components production statistics are required. The sector classification for which production statistics are composed is different from the physical flow statistics, which were presented in Section 2.2.

Monetary production statistics are available for four branches within the Dutch Energy Sector.

- DF23—cokeries and refineries, processing crude oil and hard coal;
- DF23201—refineries;
- E4000.1—central electricity and heat production;
- E4000.2/3—distribution and decentral electricity production.

The first three branches are part of the transformation sector. The fourth relates to two subsectors: transportation and distribution. No production statistics are available from Statistics Netherlands for the exploitation subsector [10].

Monetary production statistics present monetary flows to and from the branch. These flows are categorized as Production, Consumption, Value added or Company results:

- Production value includes sales, storage mutation products, and trade and other revenues.
- Consumption value includes industrial purchases, storage mutation feedstock, energy consumption costs, and other company costs.
- Value added includes labor costs, and taxes and fees.
- Company results includes net-interest, extraordinary costs/revenues, facilities, and the depreciation on fixed assets.

Thirteen different cost accounts are available to describe the monetary flows into and from the decentral and central electricity branches. For cokeries and refineries more detailed information is available: 20 costs accounts are available, wherein labor costs are specified as gross wages or salary, social insurance fees, pension and VUT fees or other expenses social services. Even more specific information is available on refineries as other company costs are specified as, e.g. rental costs, maintenance- and repair costs, aid-materials, etc. In total, monetary production statistics on refineries identify 42 different costs accounts. Each of the cost accounts is categorized as FE, CEE, LEE or ERE.

As a result of the above, EEA has been set-up for four branches of the Dutch energy sector: (1) cokeries and refineries, (2) refineries, (3) central electricity production and (4) distribution and decentral electricity production. The first step is to determine energy and exergy flows based on the mass-flow data. Table 7 presents the results.

The second step is the calculation of the capital conversion factor. Sciubba [7] proposes a national capital conversion factor, defined by the annual influx of exergy into a country divided by the economic variable M2, which is a certain amount of money available within a year to a country. The goal of a conversion factor is to express the monetary value of a certain quantity of exergy. As this paper does not analyze an entire nation but industry branches, conversion factors specific for each branch are used instead of a national capital conversion factor.

The specific capital conversion factor has been calculated as

$$K_{\mathrm{cap}} = \mathrm{FE}^{€}/\mathrm{CExC}^{\mathrm{FE}}, \tag{2}$$

Table 7
Energy and exergy flows for four branches within the Dutch Energy Sector

Branch	Input (PJ)		Output (PJ)	
	Energy	Exergy	Energy	Exergy
1. Cokeries & refineries	4978	5334	4786	5133
2. Refineries	4856	5221	4682	5022
3. Central electricity production	526	511	232	216
4. Distribution & decentral electricity production	1315	1228	1265	1184

Table 8
Capital conversion factors

Branch	$\mathrm{CExC}^{\mathrm{FE}}$ (PJ)	$\mathrm{FE}^{€}$ (mln €)	K_{cap} (mln €/PJ)
1. Cokeries & refineries	5484	8929	1.63
2. Refineries	5367	8650	1.61
3. Central electricity production	564	1309	2.32
4. Distribution & decentral electricity production	1728	8759	5.07

where $FE^{€}$ is the annual monetary value of the feedstock, and $CExC^{FE}$ represents the annual cumulative exergy value of the feedstock, of which the calculation has been explained in the previous section. The monetary value of the feedstock $FE^{€}$ is the sum of the following company costs for each branch: feedstock, energy, water, energy consumption costs, fuel costs of transportation, freight costs, and storage mutation. Table 8 shows the $CExC^{FE}$, $FE^{€}$, and specific K_{cap} values for the four branches.

The next step is to use the branch specific capital conversion factor K_{cap}, calculated from Eq. (2), to estimate the CEE, LEE and ERE value, thereby assuming this conversion factor to be branch specific but the same for all EE-terms.

The CEE is estimated by conversion of the monetary values of short- and long-term investments by using the capital conversion factor K_{cap} as follows:

$$\mathrm{CEE} = (I_{\mathrm{ST}} + \mathrm{CS}_t)/K_{\mathrm{cap}}, \tag{3}$$

where I_{ST} is short-term investment in capital goods and CS_t is the capital stock in year t (1996).

The term LEE has three contributions: the man-power equivalent exergy (LEE_W), LEE due to skills (LEE_{Skill}), and social accounts (LEE_{SA})

$$\mathrm{LEE} = \mathrm{LEE_W} + (\mathrm{LEE}^{€}_{\mathrm{Skill}} + \mathrm{LEE}^{€}_{\mathrm{SA}})/K_{\mathrm{cap}}. \tag{4}$$

For the computation of the man-power equivalent exergy, LEE_W, the annual consumption of exergy per person is set to 300 GJ [14]. The monetary value of labor, skill component, $LEE^{€}_{Skill}$, has been calculated from the monetary value of labor stock due to skills in year 1996 (process specific wages: salaries, overhead costs of general management, and non-process specific, as hired personnel and services). The term $LEE^{€}_{SA}$ equals the monetary value of social cost accounts.

Sciubba [7] defined ERE as the estimate of the exergy consumption required to neutralize the impact of waste flows entering the environment. As this paper applies EEA on sector (company) level, a remediation process to neutralize the annual waste flows of these companies together cannot be designed. Furthermore, it was not possible to disaggregate the waste flows. Within the production statistics, one account represents environmental costs: garbage and waste processing. A monetary value on this very specific account, as part of "other company costs", is only available only for branch 2, refineries. The environmental equivalent exergy is determined as

$$\mathrm{ERE} = \mathrm{ERE}^{€}/K_{\mathrm{cap}}, \tag{5}$$

where $ERE^{€}$ is the monetary cost of garbage and waste processing.

Tables 9a and b show the values of all terms contributing to the Extended Exergy for all considered branches. For all branches, it is noted that the man-power equivalent of exergy LEE_W makes the smallest contribution to the Extended Exergy. More specific, branch 2, cokeries and refineries, is dominated by the feedstock term, followed by capital, and labor, respectively. The large contribution of feedstock to the overall EE can be seen as indicator for the pressure of the production system on the environment, and the dependence

Table 9
Extended exergy and its constituent components

Branch	FE	CEE	LEE	[LEE_w	LEE_{skill}	LEE_{SA}]	ERE	EE
(a) (PJ)								
1	5484	2994	459	[2	410	47]		8937
2	5367	2846	501	[2	457	42]	4	8718
3	564	2829	153	[2	134	17]		3546
4	1728	2126	266	[8	232	26]		4120
(b) (%)								
1	61	34	5	[0	5	0]		100
2	61	33	6	[0	5	1]	0	100
3	16	80	4	[0	4	0]		100
4	42	52	6	[0	6	0]		100

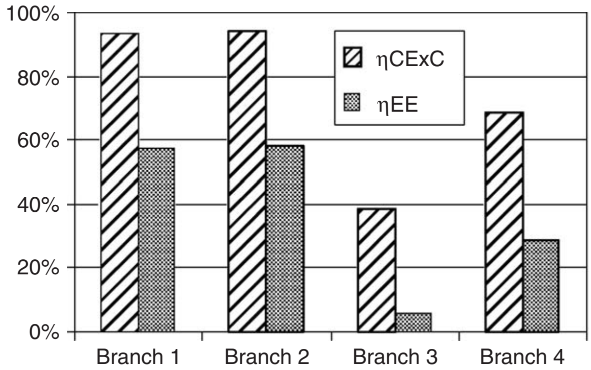

Fig. 1. CExC and EE exergy efficiency for different energy branches.

Table 10
Comparison EE values and product sales; alternative CExC values

Branch	Monetary scale		Exergetic scale		K_{cap}^{EE} (Mln €/PJ)	$CExC_{PS}^{FE}$ (PJ)
	PS (Mln €)	EE*K_{cap} (Mln €)	PS/K_{cap} (PJ)	EE (PJ)		
1	9955	14,567	6107	8937	1.11	8044
2	9606	14,036	5966	8718	1.10	7864
3	3185	8227	1373	3546	0.90	1454
4	13,064	20,888	2577	4120	3.17	2763

of the system on the environment. The branches 3 and 4 present a quite other image. Central electricity and heat production (branch 3) depends far less on feedstock (mainly natural gas, 16%) and capital goods makes up for 80% of the EE of the product, reflecting the capital-intensive character of the branch.

The performance indicator of considered energy branches can be represented as

$$\eta_{EE} = Ex_p/EE, \tag{6}$$

where Ex_p and EE are the annual chemical and extended exergy values, respectively, for every branch.

Fig. 1 shows a comparison of efficiencies for all branches based on CExC and extended exergy, respectively. The η_{EE} indicator is much lower than η_{CExC}, but also far more strict. It can be concluded that the thermodynamic performance of refineries (branch 2) is very good; $\eta_{CExC} = 94\%$, but the performance of the branch taking into account capital and labor terms, is substantially lower; $\eta_{EE} = 58\%$.

Another aim of EEA is to develop an alternative value for the product sales. A comparison between the actual monetary product sales and calculated extended exergy values is shown in Table 10. For all branches the extended exergy evaluation of the product is much higher than its product sales, which implies that the feedstock is underestimated by the monetary system.

The values of the capital conversion factor calculated from the product sales and extended exergy as $K_{cap}^{EE} = PS/EE$ are for all branches lower than K_{cap}^{FE} calculated from the monetary values $FE^{€}$ and $CExC^{FE}$ of feedstock (see Eq. (2)). As $K_{cap}^{FE} > K_{cap}^{EE}$, it means that the estimated CExC value of the feedstock, $CExC^{FE}$ is too low. A new estimate of CExC based on the product sales is calculated as $CExC_{PS} = FE^{€}/K_{cap}^{EE}$. The values of $CExC_{PS}$ are also given in Table 10. The corrected values $CExC_{PS}$ are higher than those of $CExC^{FE}$, what suggests that CExC should include not only thermodynamics, but also economical and environmental aspects.

4. Conclusions

The presented analysis of the Dutch Energy Sector shows that energy and exergy efficiencies of most subsectors are very high but the CExC efficiency is lower, accounting for the exergy consumption of the feedstock before it enters the sector. The high values of exergy indicators are explained by the fact that the presented analysis involves only conversion of primary to secondary and final energy. The conversion steps related to the useful energy are not involved.

The Extended Exergy efficiencies are much lower than those using energy-, exergy- or CExC-based indicators as economical and environmental aspects are taken into account. The application of EEA to the Dutch Energy Sector required some modifications: (a) the definition of the capital conversion factor and (b) the calculation of the ERE. The equivalent exergy of capital, labor, and environmental remediation are estimated by conversion of monetary values. Such estimation method gives equivalent exergy values, which are very sensitive to capital conversion factor. However, the presentation of the same energy accounts in monetary as well in exergetic units should contribute to a better communication between engineering and the energy policy fields.

EEA is grounded through exergy concept in thermodynamics and on the other hand, through production factors capital and labor, in economics. Moreover, environmental costs are included in this analysis. Therefore EEA seems to be a proper candidate to be used as a multidimensional indicator to analyze performance of chemical and energy transformations.

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