Sustainability performance of economic sectors based on thermodynamic indicators

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Abstract

Nowadays, various indicators of sustainability performance are used, usually grounded in economics, ecology, thermodynamics, and sociology. The main shortcoming of the commonly used indicators is their 'one-dimensional' character. This paper focuses on thermodynamic sustainability indicators, which also couple environmental and economic aspects. The performance of economic systems is evaluated using various indicators, ranging from exergy, which shows the thermodynamic efficiency, through Cumulative Exergy Consumption CExC, which couples exergy and life cycle analysis, up to Extended Exergy Accounting EEA, where also economic aspects are included. The analysis is illustrated for the Dutch energy sector and for the Dutch Society, including extraction, conversion, agriculture, industry, transportation, tertiary, and domestic sectors.

Keywords: sustainability indicators, exergy analysis, energy policy, environmental impact.

1 Introduction

In the last three decades sustainable development is considered as one of the major components of economic policies in many countries. It is generally believed that improvement in performance of various sectors, particularly industry and transportation, is a very effective way to reduce current global problems due to climate change and environmental pollution. The progress towards sustainability requires meaningful, practical, and scientifically based metrics.

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One of the difficulties with measuring sustainability is the lack of consensus on the evaluation of performance of various systems. Sustainability performance is a rather general term and in practice various performance indicators are used, usually grounded in economics, ecology, thermodynamics, and sociology. The main shortcoming of the commonly used sustainability indicators is their ‘one-dimensional’ character what means a restriction to only one performance aspect. The economic indicators measure the performance in terms of monetary values, such as energy prices. Many environmental indicators are used to express various environmental problems, such as green house effect or acidification. Traditionally, thermodynamic indicators are restricted only to exergetic efficiency, whereas economic and environmental aspects are not involved. 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 in the same units.

The purpose of this paper is to demonstrate how thermodynamic indicators can be coupled with ecological and economic aspects. The paper starts with an explanation of exergy concept, which is the base of all thermodynamic indicators. Two extensions of this concept are described: Cumulative Exergy Consumption (CExC), where exergy is coupled with life cycle analysis, and Extended Exergy Accounting (EEA), where CExC is subsequently combined with other environmental and economic issues. Section 3 demonstrates how the indicators can be applied on the sector level, namely for the analysis of the Dutch energy sector. Finally, in section 4 the application of thermodynamic indicators is illustrated on the national level to analyse the performance of the Dutch society.

2 Thermodynamic sustainability indicators

Energy-related systems are traditionally analysed by balancing the energy and mass flows of a process. The energy efficiency of a process is determined as the ratio between the actual output to the actual input. The energy concept is, however, subject to the First Law of Thermodynamics, which states that energy is conserved in a process. This implies that the output-input ratio always adds up to 100%. However, in the process energy often changes its form and quality, e.g. from mechanical work into heat what is not accounted by the energy analysis.

Exergy analysis is a successor of the traditional energy analysis. This relatively new method has recently been applied in energy and chemical technology, and other fields of engineering and science, Szargut [1]. The exergy concept is based on the Second Law of Thermodynamics, which takes into account not only the quantity of materials and energy flows, but also their quality. Due to the ‘entropy law” the quality of materials and energy always degrades in all chemical or physical processes. Exergy is defined as the maximum amount of useful work that can be obtained from a system, and among the different forms of exergy, three forms are the major contributors to the total exergy: thermal exergy, work exergy, and exergy of materials.

Contrary to the mass and energy balances, exergy is not conserved in a process. It means that the exergy leaving any process step will always be less than the exergy in and the difference is called exergy loss or irreversibility *I*. The exergy balance of a process can be represented in the following form using exergy values of all streams entering and leaving the process:

$$\sum_{IN} \mathrm{E}_j + \mathrm{E}^Q + \mathrm{E}^W = \sum_{OUT} \mathrm{E}_k + I \qquad (1)$$

where $\sum_{IN} \mathrm{E}_j$ and $\sum_{OUT} \mathrm{E}_k$ are exergy flow of all entering and leaving material streams, respectively, E^Q and E^W are the sums of all thermal exergy and work interactions involved in a process. Exergy loss (irreversibility) relates to entropy production in the system.

Exergy-based indicators have been coupled with Life Cycle analysis concepts to become a 'two-dimensional' indicator, such as Cumulative Exergy Consumption (CExC), as proposed by Szargut [1]. The CExC method values a product based on its entire life from cradle-to-grave and can be applied for production-chain analysis. In this method the net of production process is divided in four levels, comprising all material and energy streams involved in the final production process (level 1), and in the fabrication of intermediate products (level 2), as well in production of machines and installations (levels 3 and 4). The CExC-value indicates the total amount of exergy consumed per final product in the whole production chain.

CExC and exergy methods produce results of a purely technical nature that are both expressed in the same units – joules. The results of exergy evaluation are often not directly suitable for non-technical analysis where the monetary values are preferred. Recently, Extended Exergy Accounting method (EEA) has been proposed as an extension of standard exergy analysis to include also economic and environmental issues, Sciubba [2]. The extension of the classical exergy concept by capital and labor equivalents has been motivated by Sciubba by Neo-Classical Economics (NCE) where capital and labor are identified as production factors that contribute to performance. 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 production processes.

The Extended Exergy contains the following parts: feedstock exergy FE being the CExC of feedstock, capital equivalent exergy CEE, labour equivalent exergy LEE, and environmental remediation exergy ERE. The Extended Exergy can be calculated from its constituent's components:

$$\mathrm{EE} = \mathrm{FE} + \mathrm{CEE} + \mathrm{LEE} + \mathrm{ERE} \qquad (2)$$

The FE component can be calculated based on mass-flow data. In order to address the economic (CEE and LEE) and environmental (ERE) components production statistics of a sector are required. Moreover, the capital conversion factor, specific for the analysed system, has to be evaluated to express the monetary value of a certain quantity of exergy.

3 Performance of the Dutch energy sector

Methodological reasons to study the energy sector are large volumes of natural resources processed, thereby directly being relevant to environmental issues such

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as natural resource scarcity and atmospheric pollution. The analysis of the Dutch energy sector 1996 is based on mass-flow data published by the Statistics Netherlands [3]. The data allows for a breakdown into 8 branches, which are classified in three sub-sectors, as indicated below:

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

For the above-mentioned branches, the 27 mass-flow accounts of primary resources are grouped into three main categories: hard coal (products), crude oil (products), and other energy carriers (electricity, steam).

Table 1 shows the main components of the Dutch energy balance, Ptasinski *et al* [4]. The energy balance is dominated by trade as 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. Table 2 summarises the energy, exergy and CExC flows for all branches of the Dutch energy sector, calculated using the annual mass-flow data of every of the above-mentioned 27 resource account, and its net-calorific value, its specific exergy value, and a value representing its Cumulative Exergy Consumption (CExC), respectively.

Table 3 shows three efficiency indicators (η), defined as the ratio of production (output) and input, based on the three different valuations from the Table 2. 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

Table 1: Energy balance 1996 for the Netherlands.

Input (PJ)			Output (PJ)		
Exploitation		3 119	Domestic consumption		3 076
- *natural gas*	*2 891*		- *crude oil*	*2 441*	
Import		6 506	- *natural gas*	*1 598*	
- *crude oil*	*4 227*		- *crude oil products*[a]	*-1737*	
- *crude oil products*	*1 356*		Export		5 960
Bunker		- 601	- *crude oil*	*1 898*	
Stock mutation		12	- *crude oil products*	*2 485*	
			- *natural gas*	*1 464*	
Total		9 036	Total		9 036

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

sub-sectors, 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 sub-sector shows lower indicators, which is explained by a lower specific exergy value of the product compared to the feedstock.

Table 2: Energy and exergy flows for sub-sectors of the Dutch energy sector.

Sub-sector	Input (PJ)			Production (PJ)	
	Energy	Exergy	CExC	Energy	Exergy
Exploitation	3 202	3 337	3 372	3 169	3 303
Transformation	5 647	5 973	6 217	5 116	5 407
Distribution	5 625	5 942	6 649	5 595	5 904
Dutch Energy Sector	14,474	15,252	16,238	13,879	14,615

Table 3: Efficiencies for sub-sectors 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

The EEA is performed for the following four branches within the Dutch energy sector, where the production and monetary statistics are available: 1. cokeries and refineries, 2. refineries, 3. central electricity production, 4. distribution and decentral electricity production. The first three branches are part of the transformation sector and the fourth relates to two sub-sectors: transportation and distribution. Table 4 summarizes the energy and exergy data for these branches.

Table 4: Energy and exergy flows for branches within the Dutch energy sector.

Branch	Input (PJ)		Output (PJ)	
	Energy	Exergy	Energy	Exergy
1 cokeries & refineries	4 978	5 334	4 786	5 133
2 refineries	4 856	5 221	4 682	5 022
3 central electricity production	526	511	232	216
4 distribution & decentral electricity production	1 315	1 228	1 265	1 184

The components of extended exergy can be expressed both as the exergetic as well as monetary values using the capital conversion factors. The specific capital conversion factor K_{cap} has been calculated as

$$K_{cap} = FE^{€} / CExC^{FE} \tag{3}$$

where $FE^{€}$ is the annual monetary value of the feedstock, and $CExC^{FE}$ represents the annual cumulative exergy value of the feedstock. Table 5 shows the $CExC^{FE}$, $FE^{€}$, and specific K_{cap} values for the four branches. The branch-specific capital conversion factors K_{cap} are used to estimate the CEE, LEE and ERE components of the extended exergy, assuming this conversion factor to be branch specific but the same for all EE-terms. The capital equivalent exergy CEE is estimated

Table 5: Capital conversion factors for branches within the Dutch energy sector.

Branch	$CExC^{FE}$ (PJ)	$FE^{€}$ (mln €)	K_{cap} (mln €/PJ)
1. cokeries & refineries	5 484	8 929	1.63
2. refineries	5 367	8 650	1.61
3. central electricity production	564	1 309	2.32
4. distribution & decentral electricity production	1 728	8 759	5.07

by conversion of the monetary values of short and long-term investments. The component labour equivalent exergy LEE has three contributions: the man-power equivalent exergy, labour equivalent exergy due to skills, and social accounts. The Environmental Remediation Exergy ERE is defined as the exergy consumption required to neutralize the impact of waste flows entering the environment. As this section applies EEA on sector (company) level, a remediation process to neutralize the annual waste flows of these companies together cannot be designed. The ERE component is calculated only for branch 2, refineries, where within the production statistics the environmental costs are available.

Table 6 shows the values of all terms contributing to the extended exergy for all considered branches. Branches 1 and 2, cokeries and refineries, are dominated by the feedstock term, followed by capital, and labour, 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 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) 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

$$\eta_{EE} = Ex_p / EE \tag{4}$$

where Ex_p and EE are the annual chemical and extended exergy values, respectively, for every branch. Figure 1 shows a comparison of efficiencies for all branches based on cumulative exergy consumption and extended exergy, respectively. The η_{EE} indicator is much lower than η_{CExC}, but also far more strict.

Table 6: Extended exergy and its constituent components (PJ).

Branch	FE	CEE	LEE	ERE	EE
1 cokeries & refineries	5 484	2 994	459		8 937
2 refineries	5 367	2 846	501	4	8 718
3 central electricity production	564	2 829	153		3 546
4 distribution & decentral electricity production	1 728	2 126	266		4 120

It can be concluded that the thermodynamic performance of refineries (branch 2) is very good; η_{CExC} = 94%, but the performance of the branch taking into account capital and labour terms, is substantially lower; η_{EE} = 58%.

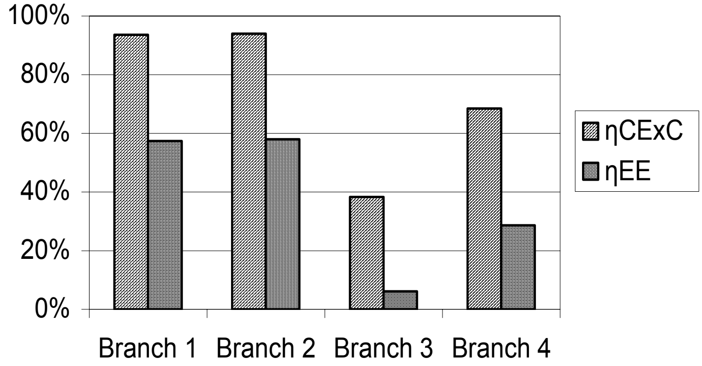

Figure 1: CExC and EE exergy efficiency for different energy branches.

4 Analysis of the Dutch society

In the last decades a number of society exergy analysis have been performed and recently the EEA has been applied for the analysis of the Italian, Milia and Sciubba [5], and Norwegian society, Ertesvåg [6]. In this section the Dutch society is analysed using energy and exergy based indicators, including EEA. To this end the country – the Netherlands as the system is divided into the following sectors: Ex–extraction (extraction of resources and raw materials from the environment), Co–conversion (energy conversion systems, including heat and power plants), Ag–agriculture (farming, herding and fishing activities, including related industry), In–industry (manufacturing industries except food industry and oil refineries), Tr–transportation (transportation of peoples and goods), Te–tertiary sector (services including government, banks, schools, commerce), and Do–domestic sector (households), as shown in Figure 2.

The system is surrounded by: E–Environment (the Earth crust, the atmosphere, the oceans, etc), and A–Abroad (other countries). All arrows between these sectors represent fluxes, which are classified as: R–primary resources (primary: fossil fuels, metals, minerals, and secondary resources: from petroleum refining, and electrical energy), N–natural resources (agricultural products, wood, livestock, fish, game), P–products (products generated by In, Tr, and Te–sectors), T–trash (waste materials deposited in the environment), D–discharge (combustion gases, thermal discharge in the environment), L–human work (labour), and C–capital (monetary flows).

The evaluation of the performance of the Dutch society in 2000 using exergy indicators is based on energy balances published by the Statistics Netherlands [2], where data on R, N, P, T, and D-fluxes are included. The capital equivalent exergy CEE (see Eq. 2) is calculated as the product of a monetary $C^{€}$-flux and

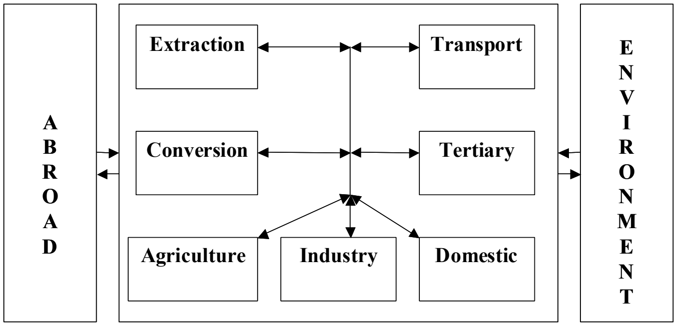

Figure 2: Model of the Netherlands as the system.

the capital conversion factor K_{cap}. The capital conversion factor K_{cap} is evaluated as

$$K_{cap} = E_{in} / M_2 \tag{5}$$

using E_{in} as the annual exergetic input to the society, and M_2 as the monetary circulation in the country. The labour equivalent exergy (see LEE in Eq. 2), being the exergetic equivalent of a monetary $L^{€}$-flux, is calculated as the product of a monetary $L^{€}$-flux, and the labour conversion factor K_{lab}. The labour conversion factor K_{lab} is evaluated as

$$K_{lab} = E_{in} / W_{tot} \tag{6}$$

using E_{in}, W_{sector} and W_{tot} as the total amount of work-hours in the sector and society, respectively. The capital flux into each sector (except the households) is taken as the sum of production, the gross investment, and net production subsidies. The capital flow out of the sectors is taken as the sum of the cost of good and services consumed in the production, compensation of employees, net product taxes, return to the owners, and gross investment. Labour is considered as an output from the household Do-sector and input to all other sectors.

In 2000, the values of E_{in}, M_2, and W_{tot} for the Dutch society are 5490 PJ, 353 billion €, and 9843 Mhr, respectively. The calculated capital and labour conversion factors for the Netherlands are: K_{cap} = 15.7 MJ/€ and K_{lab} = 557.8 MJ/hr, van der Stelt *et al* [7].

Table 7 summarizes the EE fluxes to all sectors of the Dutch society whereas Table 8 shows the conversion efficiency of individual sectors, calculated as the ratio between output to a sector including R, P, N, L, and C-fluxes, and corresponding input. The energy and exergy efficiency are very similar for every sector due to the way of accounting fluxes in this method.

The main fluxes are resources and products for which the energy and exergy values do not differ substantially.

The EE efficiency is notably larger than the exergy efficiency for almost all sectors (excluding industry) what is due to large contribution of the capital outflow with respect to capital inflow to a sector. The EE efficiency in the extraction sector is almost the same as the exergy efficiency what indicates less influence of the capital and labour factors in this sector. The extraction, conversion, and industry sectors exhibit the highest efficiency, mainly to a large throughput of exergy of resources and products. The EE efficiency of the agriculture is higher than its exergetic counterpart due to relatively high salaries in this sector. A similar situation can be observed for the transportation sector. The performance of the household Do-sector is different from other sectors what is quite characteristic in the EEA method. Within the Do-sector the extended exergy can be produced due to capital increase what can be regarded as a result of man's creativeness. From this point of view the second law of thermodynamics is not violated, as pointed by Ertesvåg [6].

Table 7: Extended exergy fluxes of Dutch sectors (PJ/year).

	Ex	Co	Ag	In	Tr	Te	Do
Input							
R	7792.3	6239.2	344.3	974.1	543.7	275.6	564.5
P	8.6	25.1	110.6	869.7	9.0	694.0	276.3
N			808.3			64.6	58.1
L	8.4	39.0	212.0	769.2	394.9	4066.8	0.0
C	194.4	563.4	1030.9	2460.6	901.1	7589.3	7154.3
Output							
R	7558.1	4974.7					
P	2.1	17.5		1328.8	296.8	238.9	41.4
N			320.6			58.1	
L							5490.2
C	218.3	680.0	1102.2	2428.9	971.4	7483.9	7223.6
T	1.3	0.1		13.8			8.1
D	36.6	319.3	17.7	80.0	28.2	7.0	37.2

Table 8: Conversion efficiencies in various sectors of the Dutch society (%).

	Ex	Co	Ag	In	Tr	Te	Do
Energy	96.8	71.9	26.6	84.9	62.8	29.7	6.0
Exergy	96.0	71.0	26.8	84.9	57.8	30.4	6.0
Extended exergy	97.1	82.6	56.7	74.1	68.6	61.3	160.0

5 Conclusion and discussion

The analysis of the Dutch energy sector shows that energy and exergy efficiencies of most sub-sectors are very high but the CExC efficiency is lower, accounting for the exergy consumption of the feedstock before it enters the sector. The EE efficiencies are much lower than those using energy, exergy or CExC based indicators as economic and environmental aspects are taken into account. The EEA of the Dutch society shows that the exergetic equivalents of capital and labour have also large influence on the efficiency in comparison with energy and exergy efficiencies, especially in the tertiary and domestic sectors. The production of EE in the Do-sector can be seen as a product of man's creativity. In all sectors, with the exception of the industry, the EE efficiency is higher than the energy and exergy efficiency. This is due to the lower capital conversion factor of the whole society, 15.7 MJ/€ as evaluated in section 4, compared to the average value of 470.4 MJ/€ for the energy sector as evaluated in section 3. The energy sector is more resource intensive and therefore the ratio of exergetic to monetary fluxes for this sector is higher that for the whole society. EEA is grounded through exergy concept in thermodynamics and on the other hand, through production factors capital and labour, 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 analyse performance of chemical and energy transformations.

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