STATIC AND DYNAMIC POLLUTION AND RESOURCE RELATED INDICES

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Keywords: Sustainability, sustainability index, pollution indicators, resource scarcity indicators, externalities, Life Cycle Assessment, thermo-ecological cost.

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Summary

One of the approaches for introducing sustainability considerations in the analysis and optimization of energy systems is the use of indicators and indices that quantify (to the extent possible) the scarcity of natural resources and the effects of energy systems on the environment and the society, both positive (e.g. job creation) and negative (e.g. pollution, health problems). The results of several efforts to define and calculate various indices are presented in this article. They come primarily from the Life Cycle Assessment, Exergy Analysis, natural and economic resource accounting, social studies and the ExternE Project. Most of the indicators and indices are dynamic, i.e. they change with time. The indicators and indices presented in this article do not constitute an exhaustive list. The research in the field is continued, which results not only in the definition of new indicators and indices, but also in frequent updating of their numerical values due to new knowledge and more accurate methods of estimation.

1. Introduction

In *Analysis and Optimization of Energy Systems with Sustainability Considerations* it is mentioned that systematic attempts are made in order to introduce *sustainability* considerations directly into the process of synthesizing, designing, and operating such systems and it is pointed out that in order to introduce these considerations quantitatively, three aspects must be taken into account, i.e.

a. the scarcity of natural resources,
b. the degradation of the natural environment,
c. the social implications of the energy system, both positive (e.g. job creation, the general welfare) and negative (effects on human health).

The quantitative treatments or approaches, which have been proposed, can be grouped into two principal ones, namely, (i) sustainability indicators and (ii) total cost function. The latter is the approach presented in the aforementioned article. The former is the subject of the present article, while some information is given also in *Life-Cycle, Environmental, and Social Considerations – Sustainability, National Exergy Accounting of Natural Resources* and *Global Exergy Accounting of Natural Resources*. These sustainability indicators (e.g. resource, environmental, and social indicators) are typically not expressed in the same units and consequently are not additive. Thus, they cannot easily if at all be introduced into an approach such as *environomics* (see *Analysis and Optimization of Energy Systems with Sustainability Considerations*). They may instead, for example, be used as non-dimensionalized indicators in a multi-criteria approach, which employs a set of weighting factors in order to calculate the value of a *general sustainability indicator* that is used in the general assessment of a system or for comparisons between systems.

It must be clarified that the definition and numerical evaluation of the various indices (or indicators) is an on-going process because not only the underlying principles have not yet been clearly understood, but also the data collected are not sufficient for an undisputable evaluation of these indices. In the following, the results of several efforts to define and calculate various indices are presented. The list is by no means exhaustive. A few indicators are presented in *Analysis and Optimization of Energy Systems with*

Sustainability Considerations and they are not repeated here.

2. The Nature of Indicators or Indices

Recording changes in our environment in a quantitative manner by means of physics, chemistry, ecology, economy, social science, etc., is one of the basic conditions to gaining insight to a natural phenomenon. This recording of changes leads to the construction of models, their parameters, and end indicators or indices. Often an intuitive proceeding leads to a preliminary definition of indicators, which must be tested. Often linear approaches will be sufficient if only "marginal" approaches have to be introduced. The increment of the temperature in the atmosphere for example may be proportional (linear) to the quantity of greenhouse gases ejected to the atmosphere. The impact indicator, Global Warming Potential (GWP), is an indicator or index of the ecology and an example of an indicator based on the constant of proportionality.

Notice that this index:

- is not a natural constant,
- is specific for each substance,
- is a reflection of the current status of (natural) science,
- is mostly a function of space and time,
- can be standardized by international standard organizations,
- is for the most part only the linear constant of a complex functional description,
- is part of an indices system, which should be chosen in a way that very little dependence between them occurs.

Such indicators or indicator systems represent parameters of a mathematical, physical or chemistry model of changes concerning the climate, soils, communities, waters (stationary and fluent), waste management, economic considerations, social behavior, nature conservation, etc.

Both ecosystems and technology change with time; their dynamics is very important for the analysis. Since environmental and resource indicators reflect the state of ecosystems and the depletion of resources, they are complex functions of time.

3. Indicators derived by the Life Cycle Assessment (LCA) Method

3.1. The LCA Method

The aim and methodology of LCA have been presented in brief in *Life-Cycle, Environmental and Social Considerations – Sustainability*, including related bibliography for further reading.

At least since the beginning of industrialization, human beings have been the source of observed, expected and predicted environmental damages, which are due to both increasing population and increasing needs. Equation (1) makes explicit the thinking behind this statement:

$$WD = P \cdot S \cdot C \cdot T \cdot I \cdot D \qquad (1)$$

where

WD	total world-wide environmental damages,
P	population,
S	service gained per person,
C	consumption per service gained,
T	throughput per consumption,
I	environmental impact per throughput,
D	environmental damage per environmental impact.

LCA is neither concerned with a regulation of the population size (*P*) nor does it question the demand for services by this population (*S*). LCA is concerned only with the environmentally efficient provision of these services. Its aim is to provide the information that makes three things possible:

- the generation of as many services as possible with the least amount of products, i.e., to have intelligently conceived products with a long life and that can be shared (factor *C*),
- the production of these products with minimal material flow, i.e., the production efficiency is maximized (factor *T*),
- the reduction, as much as possible, of environmental interventions per industrial throughput, i.e., the application of clean technology and the minimization of wastes (factor *I*).

The final factor (*D*) describes the environmental consequences of doing this in terms of damage from the environmental interventions emanating from the industrial metabolism. LCA models the environmental damage per service gained in order to either compare this ratio for alternative ways to provide the given service or to identify those processes that dominate environmental interventions.

There are two sets of LCA applications. The first set can be called the *attribution case*. In this set, the main question is which share of environmental impacts has to be attributed to which process or product. The second set can be called the *change-oriented case*. Here the question is how much the environmental impacts will increase or decrease if in the future a certain product will be produced according to an alternative design. The first is the static case, which aims to attribute all environmental impacts to all provided services. The second is the dynamic one, where the marginal cases are of interest.

Indicators derived by LCA are presented in the following.

3.2. The DALY Concept and Index

Environmental pollution may (i) cause annoyance that directly leads to a reduced quality of life, (ii) lead to transitory illnesses, e.g. asthmas, which reduce for some time the quality of life, (iii) lead to mortal illnesses, e.g. cancer, thus, shortening the average life expectancy. The DALY-method ('disability adjusted loss of life years') aims at quantifying these effects. The basis of the method consists of adding the years of life lost by premature death and the years lived in a disabled manner, where the severity of the quality reduction is expressed by a disability weight (*DW*). The World Health Organization (WHO) has published values for *DW*, establishing the equivalency of illness to lost years of life. The *DALY* index is obtained from the relation

$$DALY = YLL + YLD \cdot DW \qquad (2)$$

where

YLL years of life lost due to premature death,
YLD years of life lived disabled,
DW disability weight.

For fatal diseases (cancer) the typical age of onset of the illness and the survival time are also considered. Tables 1 and 2 report examples of values for the *DALY* index.

Illness	***YLL***	***YLD·DW***	***DALY***
Lung cancer (1)	15.8	0.3	16.1
Skin cancer (1)	3.2	0.2	3.4
40 years of chronic bronchitis		2.0 (40·0.05)	2.0
Cough (1)		0.0027	0.0027
1 year of daily sleep disturbance due to noise		0.06 (*)	0.06
1 year of daily communication disturbance due to noise		0.05 (*)	0.05
(*) *Weighting value not yet proposed by WHO, but proposed in the literature.*			

Table 1. Examples of *DALY* values for damage to human health.

Of course, in the establishment of the *DALY*-value per kg of emitted pollutant, a complete tracking of the pollutant must be taken into account, from emission to propagation, dilution or eventual decay, intake by breathing or by nutrition, to damage effects of the human body.

Substance	**Emitted into**	***DALY***	**Damage cost**	**Type of damage**
		years/kg	Euros/kg (*)	
Particles	Air	0.0015	100	Respiratory disease
NO_2	Air	0.0007	50	Respiratory disease
Cd	Air	0.0012	80	Cancer
Cd	River	0.00003	2	Cancer
CO2	Air	0.0000004	0.03	Starvation, accidents
TCDD	Air	30	2000000	Cancer
TCDD	River	10	700000	Cancer
(*) At a cost of 70000 Euros per year lost.				

*TCDD= Tetrachlor-Dibenzo-p-Dioxin

Table 2. Damage for pollutants emitted into the air or water in *DALY* and Euros per kg.

Climate change due to CO_2 is taken into account by assuming a reduction of food availability leading to forced migration and more starvation deaths, as well as additional natural catastrophic events leading to accidental deaths. Other greenhouse gases can be treated in the same manner, according to their global warming potential (e.g. for methane 23 times the value of CO_2). By assigning a cost to every lost life (e.g. 70000 Euros per year) the environmental cost due to damage to human health per unit of emitted pollutant can be evaluated (Table 2).

3.3. Environmental Burden due to Resource Use Indicator

This indicator is defined by the equation:

$$ED_{\text{res}} = \sum_i f_i m_i \quad (3)$$

where

f_i valuation weighting factor for resource *i* measured in Environmental Load Units (ELU) per unit mass of the resource *i* (ELU/kg)

m_i quantity of the resource *i* used (kg).

The total environmental burden, ED_{res}, is expressed in Environmental Load Units (ELU). Values of the factors f_i are given in the bibliography. Examples are the following:

Aluminum: $f_{\text{Al}} = 0.42$ ELU/kg
Copper: $f_{\text{Cu}} = 57$ ELU/kg
Iron: $f_{\text{Fe}} = 0.68$ ELU/kg
Mercury: $f_{\text{Hg}} = 40000$ ELU/kg

3.4. Environmental Burden due to Emission of Pollutants Indicator

This indicator is defined by the equation:

$$ED_{\text{pol}} = \sum_i d_i m_i \quad (4)$$

where

d_i valuation weighting factor for emitted substance *i* measured in Environmental

Load Units per unit mass of the emitted substance *i* (ELU/kg)
m_i quantity of the emitted substance *i* (kg).

The total environmental burden, ED_{pol}, is expressed in Environmental Load Units (ELU). Values of the factors f_i are given in the bibliography. Examples are the following:

Arsenic: $d_{Ars} = 10$ ELU/kg
Carbon dioxide: $d_{CO_2} = 0.0636$ ELU/kg
CFC-11: $d_{CFC\text{-}11} = 216$ ELU/kg

3.5. Climate Change Indicator

This indicator is defined by the equation:

$$CC = \sum_i GWP_{a,i} m_i \qquad (5)$$

where

$GWP_{a,i}$ Global Warming Potential for the emitted substance *i* integrated over the years a and measured in kg of CO_2 equivalent per unit mass of the substance *i* (kg CO_2 eq./kg)
m_i quantity of the emitted substance *i* (kg).

The total Climate Change, CC, is expressed in kg of the reference substance, CO_2. Values of the factors $GWP_{a,i}$ integrated over 20, 100 and 500 years (*a* = 20, 100, 500) are given in the bibliography. Examples are the following:

Carbon dioxide (for any number of years): $GWP_{CO_2} = 1\ \mathrm{kg_{CO_2,eq}/kg}$
CFC-11, 20 years: $GWP_{20,CFC\text{-}11} = 5000\ \mathrm{kg_{CO_2,eq}/kg}$
CFC-11, 100 years: $GWP_{100,CFC\text{-}11} = 4000\ \mathrm{kg_{CO_2,eq}/kg}$
Methane, 20 years: $GWP_{20,CH_4} = 56\ \mathrm{kg_{CO_2,eq}/kg}$
Methane, 100 years: $GWP_{100,CH_4} = 21\ \mathrm{kg_{CO_2,eq}/kg}$

3.6. Ozone Depletion Indicator

This indicator is defined by the equation:

$$OD = \sum_i ODP_{\infty,i} m_i \qquad (6)$$

where

$ODP_{\infty,i}$ steady-state Ozone Depletion Potential for the emitted substance i measured in kg of CFC-11 equivalent per unit mass of the substance i (kg CFC-11 eq./kg)

m_i quantity of the emitted substance i (kg).

The total Ozone Depletion, OD, is expressed in kg of the reference substance, CFC-11. Values of the factors $ODP_{\infty,i}$ are given in the bibliography. Examples are the following:

CFC-11: $ODP_{\infty,\mathrm{CFC-11}} = 1\ \mathrm{kg_{CFC\text{-}11,eq}/kg}$

CFC-115: $ODP_{\infty,\mathrm{CFC-115}} = 0.40\ \mathrm{kg_{CFC\text{-}11,eq}/kg}$

Halon-2402: $ODP_{\infty,\mathrm{Halon-2402}} = 7\ \mathrm{kg_{CFC\text{-}11,eq}/kg}$

4. Exergy-based Indices

Exergy can be accepted as a common quality measure of all natural resources. Therefore, the cumulative exergy consumption of non-renewable natural resources (see *Life-Cycle, Environmental and Social Considerations – Sustainability*) termed *ecological cost,* has been proposed as a measure of their depletion. Based on this cost, two indices are defined: the *thermo-ecological cost* and the *sustainability index*. They are explained in brief in the following.

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Biographical Sketch

Christos A. Frangopoulos is Professor at the School of Naval Architecture and Marine Engineering, National Technical University of Athens (NTUA), Greece.

He received the Diploma in Mechanical and Electrical Engineering from the NTUA in 1971. After his military service (1971-1973), he worked as Superintendent Engineer of ship-owning companies, and as Head of the Diagnostic Center of a ship repairing company in Greece (1973-1979).

He performed graduate studies in Mechanical Engineering with major in Thermal Sciences at the Georgia Institute of Technology, Atlanta, Ga., USA, leading to the M.Sc. degree (1980) and Ph.D. degree (1983).

He joined the School of Naval Architecture and Marine Engineering (NTUA) as a faculty member in 1985. He lectures on marine engineering, as well as marine and land-based energy systems in both undergraduate and inter-departmental graduate courses.

His research activity is related to the development and application of methods for analysis, evaluation and optimal synthesis, design and operation of energy systems (power plants, propulsion plants, heat recovery systems, cogeneration systems, etc.) by combining thermodynamic, economic and environmental considerations. Second Law (exergetic) analysis and internalization of environmental externalities are two particular subjects of this work. He has often given invited lectures on the results of his research in several countries.

Among his publications are papers in journals and international conferences, one book on cogeneration (in Greek) and an educational material on cogeneration (in English) available in electronic form on the web.

He is Associate Editor of *Energy–The International Journal*, *Energy Conversion and Management* and the *International Journal of Thermodynamics*.