SUSTAINABILITY CONSIDERATIONS IN THE MODELING OF ENERGY SYSTEMS

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Contents

Summary

During the 1970s and 1980s, extensive efforts were undertaken to increase the efficiency of energy conversion / use and to develop new technologies, which exploit alternative energy sources. In the 1990s, this changed somewhat and a part of the previous effort turned to research and development on ways of protecting the environment when developing, constructing, and operating energy conversion systems. As part of this effort, methods of analysis and optimization were developed which took into consideration not only energy use (exergy consumption) and financial resources expended (economics), but the scarcity of resources used as well as the pollution and degradation of the environment resulting from energy conversion. These effects were furthermore taken into account throughout the entire life cycle of a system, starting with its initial conception and ending with its decommissioning and a recycling of materials. This was an attempt to introduce *sustainability* considerations directly into the process of synthesizing, designing, and operating such systems. A discussion of the various methods or approaches for doing so and why Second Law considerations play an important role are outlined and discussed in the series of articles which appear under this Topic on *Sustainability Considerations in the Modeling of Energy Systems*.

1. Introduction

Second Law considerations play an important role in any evaluation of the *sustainability* of energy conversion systems. A deeper understanding of this role is essential for being able to effectively introduce such considerations into the process of synthesizing, designing, and operating energy conversion systems across their entire life cycle, i.e.

from initial conception to decommissioning and recycling. A discussion of the Second Law's role appears in *Global Implications of the Second Law of Thermodynamics*. Three *sustainability* aspects of particular importance are

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

The use of non-renewable fuel may be included in (a), but it is usually treated separately, because the quantities involved are usually much larger than those of other resources. Direct consideration of all or some of these aspects (i.e. (a), (b) and (c)) during the process of synthesis, design, and operation requires a quantitative treatment since a set of only qualitative arguments cannot effectively resolve the complex issues, which surround these aspects in energy systems. The quantitative treatments or approaches, which have been proposed, can be grouped into two principal ones, namely, (i) *sustainability indicators* and (ii) *total cost functions*. The latter is the approach used in *environomics* and is explained in some detail along with a number of analysis and optimization examples in *Analysis and Optimization of Energy Systems with Sustainability Considerations*. The former is explained in some detail in *Life-Cycle, Environmental, and Social Considerations – Sustainability*, *Static and Dynamic Pollution and Resource-Related Indices*, *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*. 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 an overall assessment of a system or for comparisons between systems.

Finally, none of the above approaches has as of yet been fully developed nor has all the data required for complete analyses become available. In fact, issues of data completeness as well as the necessity to continually update it continue to plague efforts of effectively and objectively introducing sustainability considerations quantitatively into the development and operation of energy systems. That being said, it nonetheless behooves us to make the effort since it is only with this additional information that we will be able to arrive at energy systems, which fit into a sustainability framework. Consequently, a considerable effort is required at an international level in order for sustainability considerations to be fully integrated into energy systems synthesis, design, and operation.

2. Expansion of the Meaning of "Optimal System" – Sustainability

Life-Cycle, Environmental, and Social Considerations – Sustainability which addresses the topic of this section expands the meaning of "optimal system" to include environmental, monetary and social externalities as decision variables and/or constraints in process optimization procedures (see *Optimization Methods for Energy Systems* and

Design and Synthesis Optimization of Energy Systems). Thus, the analysis is expanded to include the entire ecosystem in space and the life-cycle of the system in time. A number of methods which treat such externalities are examined including *Embodied Energy Analysis (“EE”)*, *Emergy Analysis (“EmA”)*, *Life Cycle Analysis (“LCA”)*, *Exergetic Life Cycle Analysis (ELCA)*, the *Cumulative Exergy Content Method (“CEC”)*, and *Extended Exergy Accounting (“EEA”)*. For the reasons which follow, the first three are the least promising of these methods since they suffer from a number of fundamental drawbacks. For example, *EE* i) maintains two separate quantifiers, energy and money; ii) does not distinguish between different forms of energy; iii) does not correctly account for environmental costs since only the “downstream” portion is actually quantified; and iv) entirely neglects the intrinsic energetic value of materials in the Earth’s crust. *EmA*, on the other hand, i) is unable to properly account for the different quality of diverse energy carriers; ii) fails to correctly account for different types of low-entropy energy flows; and iii) is doomed to failure in its application to industrial scenarios by the very high degree of approximation intrinsic in the calculation of energy transformations. Finally, *LCA* also has a number of limitations including i) its lack of economic considerations; ii) no uniformity in approach or method for applying LCA; iii) assumptions and subjective valuation procedures which are not always clearly delineated; and iv) an inability to correctly assess thermodynamically both the resource base and its final end use.

Thus, for a number of reasons including that they suffer from none or only some of the limitations outlined above, *ELCA*, *CEC* and *EEA* are the more promising of the methods examined in *Life-Cycle, Environmental, and Social Considerations – Sustainability* and are, thus, discussed in this article in more detail as is the issue of *sustainability*. Note that all three depend on the use of *exergy* and *exergy methods* of analysis and as a result are able to i) distinguish between different forms of energy on the basis of their quality; ii) able to correctly account for different types of low-entropy energy flows; and iii) able to correctly assess thermodynamically both the resource base and its final end use. As to the issue of *sustainability*, the conclusions drawn are that in order to achieve high degrees of sustainability in the development and operation of energy conversion systems, a major shift in both resource mix and end-use consumption standards using decision-support tools similar to *ELCA*, *CEC* or *EEA* is required.

3. Pollution and Resource-related Indices

Static and Dynamic Pollution and Resource-Related Indices reviews a number of the most prevalent *sustainability indicators* in the literature. As mentioned in the Introduction above, these *sustainability indicators* (resource, environmental, and social) 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 can, however, be used as non-dimensionalized indicators in a multi-criteria approach used in an overall assessment of a system or for comparisons between systems. Such indicators represent parameters of a mathematical model of the physical or chemical changes occurring in the systems or environment due to interactions which occur with the energy system which is being synthesized, designed and/or operated. Typical characteristics which these indicators have are that they i) are not natural constants; ii) are specific to a given substance (e.g., a pollutant or a natural resource); iii) reflect the current status of natural science and technology; iv) are usually a function of space and time; v) can be standardized; vi) are constants of the linear terms of more complex, nonlinear descriptions; and vii) function as part of an overall system of independent (at least to the extent possible) indices.

For example, a number of factors are used in Life Cycle Analysis (LCA) to quantify consumption per service gained (C), throughput per consumption (T), environmental impact per throughput (I), and environmental damage per environmental impact (D). This is done in order to determine the environmental efficiency of the service (or product) gained and find alternative ways of providing (not necessarily limiting) the service or of identifying processes that dominate environmental interventions. To quantify environmental damage and impact, the LCA derived *DALY indicator* or *index* is used to describe reductions in the quality of life and in shortened life expectancies.

Other indicators or indices are used to quantify the depletion of non-renewable resources such as the *thermo-ecological cost* and the *sustainability index* which are derived from the *ecological cost* which is part of the *Cumulative Exergy Consumption Method* (see *Life-Cycle, Environmental and Social Considerations – Sustainability*) for non-renewable resources. The *thermo-ecological cost* is an exergy-based indicator which results from a set of balance equations which account for the deleterious affect which the waste products of a given process or set of processes has on the global or regional environment, while the *sustainability index* is a measure of the non-renewable exergy expended in the production process of some product.

Non-exergy-based resource indicators include the *Possible Consumption Indicator (PCI)* which measures the maximum consumption of a resource over a given period of time without diminishing the resource. This is possible due to the fact that with time proven reserves of resources tend to increase as the technology required to extract them improves and/or new reserves are found. Another of these indicators is the *Current Consumption Indicator (CCI)*. It also uses the maximum consumption used by the *PCI* but divides it into the actual consumption of the resource, thus, forming a ratio that also accounts for the efficiency of the energy conversion process, which utilizes the resource. An indicator which is based on the product of the *PCI* and *CCI* is the *Resource Depletion Indicator (RDI)* which measures the change in scarcity of the resource due to resource depletion.

Now, in order to access the *sustainability* characteristics of a variety of energy systems, a number of other indicators can be used, namely, the *Resource Indicator (RI)*, the *Environmental Indicator (EI)*, *Social Indicators (SI*s*)*, and *Economic Indicators (EcI*s*)*. The first of these is a measure of the total quantity of a particular resource (fuel and materials) used to the useful energy produced during the lifetime of a system. In a similar vein, the *EI* is a measure of the total of a particular effluent ejected by a system to the useful energy produced during a system's lifetime. Among the *SI*s, which quantify the societal effects of different options for covering energy needs, are the *New Job Indicator* (SI_{job}) which is a measure of the paid new job hours corresponding to a particular energy option while the *Standard of Living Indicator* (SI_{Stl}) measures the amount of created capital corresponding to the same energy option. Similar to this last indicator are two of the *EcI*s which also measure the effects of capital, i.e. the *Capital Investment Indicator* (EcI_{inv}) which is the ratio of the capital investment to the useful energy produced for a given option and the *Cost Economic Indicator* (EcI_{cost}) which is the total cost (capital plus fuel) to the useful energy produced. A third *EcI* is the *Community Economic Indicator* (EcI_{com}) which measures the gross national product in terms of the useful energy produced.

Finally, a number of additional indicators have also been derived and come from the ExternE Project, which was a direct result of the 1992 Maastricht Treaty establishing the European Union. These indicators are part of an overall methodology called the *Impact Pathway* or *Damage Function Methodology (IPM* or *DFM)* for characterizing technologies with respect to their level of emissions, the degree of dispersion of said emissions, the impact of these emissions on the populations affected, and the economic costs which these emissions engender. *IPM* or *DFM* expresses all of its damage costs as a function of the emissions and are site specific.

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Biographical Sketch

Michael R. von Spakovsky is Professor of Mechanical Engineering and Director of the Center for Energy Systems Research at Virginia Polytechnic Institute and State University, Blacksburg, VA. He has 17 years of teaching/research experience and 17 years of industry experience. He teaches undergraduate and graduate level courses in thermodynamics, kinetic theory, fuel cell systems, and energy system design. His research interests include computational methods for modeling and optimizing complex energy systems, methodological approaches for the integrated synthesis, design, operation, control, and diagnosis of such systems (stationary power as well as, for example, high performance aircraft systems), theoretical and applied thermodynamics with a focus on the unified quantum theory of mechanics and thermodynamics, and fuel cell applications for both transportation and distributed power generation. He has published widely in scholarly journals, conference proceedings, etc. (over 150 publications) and has given talks, seminars and short courses (e.g., on fuel cells) worldwide. Included among his various professional activities and awards is membership in the AIAA, *Fellow of the ASME*, member of the *Executive Committee* for the ASME's Advanced Energy Systems Division, elected member of Sigma Xi and Tau Beta Pi, Associate Editor of the *International Journal of Fuel Cell Science and Technology*, Editor-in-Chief of the *International Journal of Thermodynamics*, and Chairman of the *Executive Committee* for the *International Center of Applied Thermodynamics*.