ANALYSIS AND OPTIMIZATION OF ENERGY SYSTEMS WITH SUSTAINABILITY CONSIDERATIONS

Michael R. von Spakovsky
Virginia Polytechnic Institute and State University, USA

Christos A. Frangopoulos
National Technical University of Athens (NTUA), Greece

Keywords: energy, exergy, environment, economics, environomics, analysis, optimization, district heating, heat pumps, gas turbines, gas engines, furnaces, cogeneration, sustainability, pollution, externalities

Contents

UNESCO – EOLSS SAMPLE CHAPTERS

Summary

The construction and operation of energy systems not only consumes fuel and other scarce natural resources, but also has adverse effects on the environment. Therefore, the analysis, evaluation and optimization of energy systems must take sustainability issues into consideration quantitatively. For this purpose, three aspects must be taken into account: (a) the scarcity of natural resources, (b) the degradation of the natural environment, and (c) the social implications of the energy system, both positive and negative. For a quantitative treatment of these aspects, there are two principal approaches: (i) sustainability indicators, (ii) total cost function. The latter approach is presented in this article, since it has been used for the evaluation as well as the optimal synthesis, design and operation of energy systems. The theoretical formulation of the method is described and four numerical examples are presented. It is shown that sustainability aspects quantitatively taken into consideration have a strong impact on the decisions regarding system selection, design and operation.

1. Introduction

Not only is the transformation and use of energy resources necessary for the maintenance of life, it is equally necessary for maintaining the standards of living which can help ensure the existence of societies sufficiently stable and, thus, sufficiently able of providing the greatest political, social, and material benefits to the greatest number of people possible. However, due to accompanying adverse effects on the environment and society, energy's transformation and use is one of the major threats to the sustainability of life on earth. Consequently, it is imperative to minimize these effects by taking them into account when designing, constructing, and operating energy systems.

In the field of energy, extensive efforts were undertaken during the 1970s and 1980s to increase the efficiency of energy conversion/use and to develop new technologies that exploit alternative energy sources. Of primary concern was the depletion of energy (exergy) resources. To help these efforts, the fields of thermoeconomics and exergoeconomics, which combine thermodynamic and economic considerations in the analysis and optimization of energy systems, saw rapid growth and helped increase plant efficiencies without jeopardizing a plant's economic viability. Resulting increases in efficiency, furthermore, led to decreases in some adverse environmental effects since certain pollutant emissions such as CO_2 increase or decrease directly with plant efficiency. However, emission reductions were not the principal driving force behind this activity.

In the 1990s, this changed 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 that took into consideration not only energy use (exergy consumption) and financial resources expended (economics), but the scarcity of resources used as well as pollution and degradation of the environment resulting from energy conversion. Furthermore, these effects were 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. The term environomics appeared in the

UNESCO – EOLSS SAMPLE CHAPTERS

literature to express the fact that environmental consequences were being taken "quantitatively" into consideration along with energy resource use and economics in the analysis and optimization of energy systems. This was an attempt to introduce sustainability considerations directly into the process of synthesizing, designing, and operating such systems.

In order to introduce such considerations, three aspects must be taken into account:

(a) the scarcity of natural resources
(b) the degradation of the natural environment
(c) the social implications of the energy system, both positive (for example, 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 ((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 that surround these aspects in energy systems. The quantitative treatments or approaches that have been proposed, can be grouped into two principal ones, namely, (i) sustainability indicators and (ii) total cost function. The latter is the approach used in environomics and will be explained in some detail below since this approach has been used to directly affect the synthesis, design, and operation of specific energy conversion technologies. It will be accompanied by a number of analysis and optimization examples. These sustainability indicators (for example, 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 multicriteria 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.

Finally, neither of the above approaches has as of yet been fully developed nor has all the data required for complete analysis become available. In fact, issues of data completeness as well as the necessity continually to 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 that 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. The Environomic Optimization Problem

UNESCO – EOLSS SAMPLE CHAPTERS

©*Encyclopedia Of Life Support Systems* (EOLSS)

2.1. Statement of the Problem and its Objective or Figure of Merit

The objective or figure of merit used in environomics consists of a net total cost function which may include costs for some or all of the following: the extraction of raw materials, the manufacture of equipment, the construction of the plant, operation, resources, the dismantling of used-up equipment, the recycling of material, and environmental (including social) damage at some or all of the stages just cited. Thus, from a sustainability standpoint, the net total cost of an energy system and its associated optimization problem for synthesis, design, and operation is expressed as follows:

$$\underset{\mathbf{x},\mathbf{w},\mathbf{z}}{\text{minimize}}\ C_{\text{net tot}}(\mathbf{x},\mathbf{w},\mathbf{z}) = C_{\text{int gen}}(\mathbf{x},\mathbf{w},\mathbf{z}) + C_{\text{int env}}(\mathbf{x},\mathbf{w},\mathbf{z}) + \int_t \dot{C}_{\text{ext env}}(\mathbf{x},\mathbf{w},\mathbf{z})\,dt$$
$$+\int_t \dot{C}_{\text{res}}(\mathbf{x},\mathbf{w},\mathbf{z})\,dt - \int_t \dot{B}(\mathbf{x},\mathbf{w},\mathbf{z})\,dt \qquad (1)$$

subject to:

$$h_j(\mathbf{x},\mathbf{w},\mathbf{z}) = 0 \qquad j = 1,\ldots,J \qquad (2)$$

$$g_k(\mathbf{x},\mathbf{w},\mathbf{z}) \geq 0 \qquad k = 1,\ldots,K \qquad (3)$$

where it is noted that all the additive terms in the net total cost function can be measured either in physical units (physical economics, for example, kg of material, kJ of energy, kJ of exergy, and so on) or in monetary units (monetary economics) and where

x Set of independent variables for operation optimization (load factors of components, mass flow rates, pressures and temperatures of streams, and so on).

w Set of independent variables for design optimization (nominal capacities of components, mass flow rates, pressures and temperatures of streams, and so on).

z Set of independent variables for synthesis optimization; there is only one variable of this type for each component, indicating whether the component exists in the optimal configuration or not; it may be a binary (0 or 1), an integer, or a continuous variable such as the rated power of a component, with a zero value indicating the non-existence of a component in the final configuration.

h_i(**x,w,z**): Equality constraint functions, which constitute the simulation model of the system and are derived by an analysis of the system (energetic, exergetic, economic, and so on).

g_j(**x,w,z**): Inequality constraint functions corresponding to design and operational limits, state regulations, safety requirements, and so on.

UNESCO – EOLSS SAMPLE CHAPTERS

The first term to the right of the equals in Equation (1) is the internal general cost, that is, the cost associated with capital, and is the cost of the energy supply, excluding the cost of resources and environmental protection, while the second term is the internal environmental cost, which consists of the cost of equipment installed for pollution abatement within the energy system. The third term above is the internalized external environmental (including social) cost and is an attempt at quantifying the adverse effects of an energy system on the environment and on society. This cost may include not only external environmental costs due to the operation of the system but those due to the manufacture and dismantling/recycling of the capital equipment as well as the resources used in the system. This external environmental cost is, of course, difficult to assess; but current research in this area has made progress so that even though the research is not complete, and results to date may be disputable, it may indeed be better to account for this cost, subject to a sensitivity analysis, than to ignore it entirely. A brief discussion of how these costs are formulated and internalized into an environomic model is given in Section 2.2.

As to the resource cost (the fourth term above), it is principally based on current prices, which in turn are based on the market and, thus, reflect short-term considerations such as extraction, processing, delivery, and current scarcity only. However, a quantity of raw material extracted today has at least two long-term consequences: (i) it will not be available for future generations, and (ii) it will cause future generations to spend more energy for extracting any remaining quantities. Current market prices reflect today's costs of extraction and present or near-term supply and demand but do not, in general, account for long-term local or global scarcity or the ensuing difficulties and costs of extraction that this type of scarcity entails. Some methods, which provide a correction for the deficiency in current prices, introduce properly defined scarcity factors. A brief discussion of these factors as well as measures of scarcity is given in Section 2.3.

The final term in Equation (1) is the benefit, which the system experiences, due to the sale of its products to the outside world. This term may or may not be included in the objective function or figure of merit for the optimization problem, depending on the nature of the application involved, that is, depending on whether or not this represents a variable quantity and, thus, affects the optimization or a fixed quantity and, thus, does not.

Finally, it is noted that mass is not destroyed but always exists somewhere in nature. One may argue that if sufficient exergy were available, useful material could be recovered (by recycling, reprocessing, and so on), thus, closing the cycle of its production and use in a never-ending procedure. To the extent that this is valid, the scarcity of resources is translated into exergy for re-production. (Recycling and reprocessing cannot, of course, bring back 100% of the material used. As written by Nicholas Georgescu-Roegen:

Available matter also becomes unavailable. … Because of the finitude of our existence, we cannot recycle the rubber molecules dissipated from automobile tires, the copper molecules dissipated from coins, … and so on down the line.

UNESCO – EOLSS SAMPLE CHAPTERS

We could add here: because of the finitude of the exergy, reprocessing or substitution may not be able to cover the difference.) Similarly, if sufficient exergy were available, the adverse effects of the system on the environment could be neutralized and the environment could be restored to its initial state (with exceptions such as irreversible damage to human health). Thus, exergy is established as a unifying measure of all the terms in the total cost function when expressed in physical units (physical economics). In this way, the second law of thermodynamics and the concepts introduced with it (entropy and exergy) play a vital role in sustainability considerations for energy systems.

-
-
-

TO ACCESS ALL THE **37 PAGES** OF THIS CHAPTER,
Visit: http://www.eolss.net/Eolss-sampleAllChapter.aspx

Bibliography

Afgan N.H., Carvalho M.G. and Hovanov N.V. (1999). Energy system assessment with sustainability indicators. *Energy Policy* **28**, 603–612. [Sustainability indicators are defined and used for energy systems assessment.]

Borchiellini R., Cali M. and Santarelli M. (2000). Analysis of Extended Environomic Cost Influence on Conventional Energy Systems Design, Proceedings of the Advanced Energy Systems Division, Orlando, Florida, November 5–10, 2000. *ASME* **40**. (eds. S. Carimella, M. von Spakovsky and S. Somasundaran) pp. 259–66. [The paper analyzes how the application of an extended environomic procedure, based on the charges linked to the pollutant activities of energy system, influences the design of the system.]

Botero E. (2000). *Valoracion Exergética de Recursos Naturales: Minerales, Agua y Combustibles Fósiles*. Doctoral Thesis, University of Zaragoza, Spain. [Introduces and develops the concepts of exergetic abatement cost and exergetic reposition cost.]

Curti V., von Spakovsky M.R. and Favrat D. (1998). *An Environomic Approach for the Life Cycle Modeling and Optimization of a District Heating Network Based on Centralized and Decentralized Heat Pumps (Part I: Methodology),* International Conference on Energy and the Environment (ICEE'98), Shanghai, China, May 2–4. [Outlines a comprehensive methodology for taking into account the effect of environmental and life cycle considerations in the synthesis/design optimization of a district heating network based on centralized and decentralized heat pumps.]

Curti V., Favrat D. and von Spakovsky M.R. (1998). *An Environomic Approach for the Life Cycle Modeling and Optimization of a District Heating Network Based on Centralized and Decentralized Heat Pumps (Part II: Application),* International Conference on Energy and the Environment (ICEE'98), Shanghai, China, May 2–4. [Applies the methodology outlined in the precious publication to the synthesis/design optimization of a district heating network based on centralized and decentralized heat pumps.]

Curti V., von Spakovsky M.R. and Favrat D. (2000). An environomic approach for the modeling and optimization of a district heating network based on centralized and decentralized heat pumps, cogeneration and/or gas furnace (Part I: Methodology), *International Journal of Thermal Sciences* **39**(6), June. [Outlines a comprehensive methodology for taking into account the effect of environmental and life cycle considerations in the synthesis/design optimization of energy systems in general. It is partially the source of the environomic theory presented above in Section 2 of the present Article.]

Curti V., Favrat D. and von Spakovsky M.R. (2000). An environomic approach for the modeling and optimization of a district heating network based on centralized and decentralized heat pumps, cogeneration and/or gas furnace (Part II: Application*), International Journal of Thermal Sciences* **39**(6), June. [Applies the methodology outlined in the precious publication to the synthesis/design optimization of a district heating network based on centralized and decentralized heat pumps, cogeneration and/or a gas furnace. It is the source of the example presented above in Section 7.3 of the present Article.]

Eto J. H. and Helcke G. (1991). *Internalizing Environmental Costs: A Survey of Progress in Estimating the External Environmental Costs of Electricity Production and a Review of Market-based Policies to Incorporate Them.* Final Report EUR 13323 EN, Commission of the European Communities, Joint Research Centre, Ispra Establishment. Luxembourg: European Commission, Directorate-General Telecommunications, Information Industries and Innovation. [One of the first reports on environmental cost estimation.]

ExternE (1995). *Externalities of Energy*. European Commission, Directorate-General XII, Vols. 1–6. 2333 pp. [One of the most systematic attempts to estimate external environmental costs performed by a joint effort of many European countries. The work has been continued. The latest information as well as complete reports can be found in the web-site address: http://externe.jrc.es]

Frangopoulos C.A. (1991*). Introduction to Environomics. Symposium on Thermodynamics and Energy Systems*, (eds. G.M. Reistad, et al.), 1991 ASME Winter Annual Meeting, Atlanta, Ga. December 1-6, AES-Vol. 25/HTD-Vol. 191, 49–54, New York: ASME. [The method of thermoeconomic analysis and optimization is further developed to include environmental considerations. The term 'environomics' is proposed for this method.]

Frangopoulos C.A. (1992). *An Introduction to Environomic Analysis and Optimization of Energy-Intensive Systems*. International Symposium on Efficiency, Costs, Optimization and Simulation of Energy Systems, ECOS 1992 (eds. A. Valero and G. Tsatsaronis), Zaragoza, Spain, June 15–18, 231–239, New York: ASME. [A continuation of the work presented previously (Frangopoulos, 1991) including also an application example. It is the source of the example presented above in Section 7.1 of the present Article.]

Frangopoulos C.A. and von Spakovsky M.R. (1993). A global environomic approach for energy systems analysis and optimization. Part I. *Energy Systems and Ecology ENSEC 1993* (eds. J. Szargut et al.), Cracow, Poland, July 5–9, 123–132. [One of the first attempts to take scarcity of natural resources and environmental pollution quantitatively into consideration in the analysis and optimization of energy systems. It is partially the source of the environomic theory presented above in Section 2.0 of the present Article.]

Frangopoulos C.A. (1998). Environmental considerations in the analysis and optimization of energy systems. *Contemporary Problems of Thermal Engineering* (eds. Z. Rudnicki et al.). Poland: Gliwice-Ustron, 2–4 September, 97–111. [A brief overview of the subject. It is the source of the example presented above in Section 6.2 of the present Article.]

Frangopoulos C.A. and Caralis Y.C. (1997). A Method for taking into account environmental impacts in the economic evaluation of energy systems. *Energy Conversion and Management* **38**(15–17), 1751–1763. [A method based on the net present cost or value including environmental externalities is developed and used for evaluation of energy systems. Useful indicators such as the unit cost of pollution abatement and the critical cost of pollution penalty are determined. It is the source of the example presented above in Section 6.1 of the present Article.]

Holdren J. (1978). Environmental impacts of energy production and use: a framework for information and analysis. *Energy Information* (ed. W. Hogan), Palo Alto, California: Institute for Energy Studies, Stanford University. [Conceptual development of an analytical framework for organizing the causal linkages underlying the environmental impacts of energy technologies.]

Valero A., Lozano M.A., Serra L., Tsatsaronis G., Pisa J., Frangopoulos C. and von Spakovsky M. R. (1994). CGAM problem: definition and conventional solution. *Energy* **19** (3), 279–286. [A simple gas turbine serves as an example of applying various optimization methods. The paper describes the problem and gives the solution obtained by direct application of an optimization algorithm. Four accompanying papers published in the same volume apply various methods for solution of the same problem. A very instructive series of papers.]

UNESCO – EOLSS SAMPLE CHAPTERS

von Spakovsky M.R. and Frangopoulos C.A. (1993). A global environomic approach for energy systems analysis and optimization - Part II. *Energy Systems and Ecology ENSEC 1993* (eds. J. Szargut et al.), Cracow, Poland, July 5–9, 133–144. [The second part of a series of two papers described above (Frangopoulos and von Spakovsky 1993).]

von Spakovsky M.R. and Frangopoulos C.A. (1994). The environomic analysis and optimization of a gas turbine cycle with cogeneration. *Thermodynamics and the Design, Analysis and Improvement of Energy Systems* (ed. R. G. Krane), AES-Vol. **33**, pp. 15–26, New York: ASME, 1994. [The effect of environmental considerations on the optimization of the plant described in Valero et al. (1994) is studied. It is the source of the example presented above in Section 7.2 of the present Article.]

Szargut J., Morris D.R. and Steward F.R. (1988). *Exergy Analysis of Thermal, Chemical and Metallurgical Processes*. 332 pp. New York: Hemisphere Publishing Corporation. [This book presents the theory and applications of exergy analysis and in particular of the cumulative exergy consumption CexC mentioned above in Section 2.3 of the present Article].

Szargut J. (1999). *Depletion of the Unrestorable Natural Exergy Resources as a Measure of the Ecological Cost*. Proceedings of International Conference on Efficiency, Costs, Optimization, Simulation and Environmental Aspects of Energy Systems, Tokyo, pp. 42–45. [This paper contains the definition of an ecological cost and presents methods for its calculation].

UNESCO – EOLSS SAMPLE CHAPTERS

Biographical Sketches

Michael R. von Spakovsky is Professor at the Department of Mechanical Engineering and Director of the Energy Management Institute at the Virginia Polytechnic Institute and State University, Blacksburg, Virginia, USA.

He has over 13 years of teaching and research experience in academia and over 17 years of industry experience in mechanical engineering, power utility systems, aerospace engineering, and software engineering. He was at NASA from 1970 to 1974, in the power utility industry from 1974 to 1989, and at the Swiss Federal Institute of Technology from 1989 to 1996.

He teaches courses in thermodynamics, industrial energy systems, fuel cell systems, and energy system design. His research interests and activities include computational methods for modeling and optimizing complex energy systems, methodological approaches for the integrated synthesis, design, operation, and diagnosis of such systems (stationary power as well as high performance aircraft systems), theoretical non-equilibrium and equilibrium thermodynamics as well as 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. (approximately 100 publications) and has given talks, seminars, and short courses worldwide.

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

C. A. Frangopoulos 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, USA, leading to the MSc degree (1980) and PhD degree (1983).

He joined the Department 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 more than 40 papers in journals and international conferences and one book on cogeneration (in Greek).

UNESCO – EOLSS
SAMPLE CHAPTERS