EVALUATING ENERGY AND GREENHOUSE GAS TECHNOLOGIES WITH THE PRINCIPLES OF THERMODYNAMICS

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ABSTRACT

Many suggest that the environmental impact of energy resource use and the achievement of increased efficiency are best addressed by considering the thermodynamic property exergy. This paper reports on the use of the principles of thermodynamics via exergy to evaluate energy systems and greenhouse gas technologies. Exergy is described and its use as a tool to improve efficiency illustrated. The environmental implications of exergy are discussed, and the ties between exergy and economics described. It is concluded that thermodynamics, and particularly exergy, has a significant role to play in evaluating energy and greenhouse gas technologies. Exergy should prove useful to engineers and scientists, as well as decision and policy makers. To increase the acceptance of exergy, further research is needed to better define its role in the area of environmental impact.

1. INTRODUCTION

In the 1970s, the relationship between energy and economics was a prime concern but environment issues did not receive much attention. As environmental impacts, such as global climate change, ozone depletion and acid rain, became of concern in the 1980s, the link between energy utilization and the environment became more recognized [1,2]. Since then, there has been increasing attention to this connection, as it has become clear that energy processes (e.g., production, conversion, transport and use) affect the earth's environment [3], and that environmental impacts are associated with thermal, chemical and nuclear emissions. Although energy processes provide benefits to humanity, concerns have been expressed about the non-sustainable nature of human activities, and effort has been expended on developing methods for achieving sustainable development.

The above topics are related. The environmental impact of emissions can be reduced by increasing the efficiency of resource utilization. Increasing efficiency also has sustainability implications as it lengthens the lives of existing resource reserves. Although increasing efficiency generally entails greater use of materials, labor and more complex devices, the additional cost may be justified by the resulting benefits.

Many suggest that the impact of energy resource utilization on the environment and the achievement of increased resource-utilization efficiency are best addressed by considering exergy [4-9]. The exergy of an energy form or a substance is a measure of its usefulness or quality. Exergy is based on the first and second laws of thermodynamics, and combines the principles of conservation of energy and non-conservation of entropy. Exergy also is a measure of potential to cause change. The latter point suggests that exergy may be, or provide the basis for, an effective measure of the potential of a substance or energy form to impact the environment. Although many studies have been published in recent decades on the relation between energy and the environment [e.g., 1-3], there has only recently been an increase in work reported on exergy and the environment [e.g., 9-20].

In practice, the author feels that those working in the area of energy systems and the environment require an understanding of exergy and the insights it can provide into the efficiency, environmental impact and sustainability of energy systems. Furthermore, as energy policies increasingly play an important role in addressing sustainability issues and a broad range of local, regional and global environmental concerns, policy makers also need to appreciate the exergy concept and its ties to these concerns.

In this paper, which extends ideas presented by the author in earlier works [18-20], we consider the use of the principles of thermodynamics via exergy to evaluate energy systems and greenhouse gas technologies. The primary objective is to explain the benefits in addressing the environmental impacts, particularly those relating to greenhouse gases, using thermodynamic principles in general and the concepts associated with exergy in particular. In line with this objective, this paper goes on to describe exergy and to illustrate its use as a tool to improve efficiency. Next, the environmental implications are discussed of exergy, which relate to greenhouse gases and other environmental pollutants and impacts. Finally, the ties between exergy and economics, which are important given the interrelations between technical, environmental and economic issues, are described.

2. EXERGY

Exergy is defined as the maximum amount of work which can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment. Exergy is a measure of the potential of the system or flow to cause change, as a consequence of not being completely in stable equilibrium relative to the reference environment. Unlike energy, exergy is not subject to a conservation law (except for ideal, or reversible, processes). Rather exergy is consumed or destroyed, due to irreversibilities in any real process. The exergy consumption during a process is proportional to the entropy created due to irreversibilities associated with the process.

For exergy analysis, the characteristics of the reference environment must be specified completely. This is commonly done by specifying the temperature, pressure and chemical composition of the reference environment. The results of exergy analyses, consequently, are relative to the specified reference environment, which in most applications is modelled after the actual local environment. The exergy of a system is zero when it is in equilibrium with the reference environment. This tie between exergy and the environment has implications regarding environmental impact that are discussed subsequently.

Exergy analysis is a methodology that uses the conservation of mass and conservation of energy principles together with the second law of thermodynamics for the analysis, design and improvement of energy and other systems. The exergy method is useful for improving the efficiency energy-resource use, for it quantifies the locations, types and magnitudes of wastes and losses. In general, more meaningful efficiencies are evaluated with exergy analysis rather than energy analysis, since exergy efficiencies are always a measure of the approach to the ideal. Therefore, exergy analysis identifies the margin available to design more efficient energy systems by reducing inefficiencies. Many engineers and scientists suggest that thermodynamic performance is best evaluated using exergy analysis because it provides more insights and is more useful in efficiency improvement than energy analysis. Exergy analysis is discussed further for many processes and systems elsewhere [4-9].

3. IMPROVING EFFICIENCY WITH EXERGY ANALYSIS: ILLUSTRATION

The use of exergy methods to analyze a device so as to permit its performance to be better understood and its efficiency improved is demonstrated for the process of electricity generation using a coal-fired steam power plant.

3.1. Description of the Power Plant

The plant considered is the coal-fired Nanticoke generating station, which has been operating since 1981 in Ontario, Canada. Each of the eight units in the station have net outputs of 505 MWe. A single unit of the electrical generating station is illustrated in Fig. 1, and consists of four main sections [19,21]:

a) *Steam Generators*: Pulverized-coal-fired natural circulation steam generators combust coal to produce primary and reheat steam. Air is supplied to the furnace by motor-driven forced draft fans, and regenerative air preheaters are used. The flue gas passes through an electrostatic precipitator and exits the plant via multi-flued chimneys.
b) *Turbine Generators and Transformers*: The steam produced passes through a turbine generator, which is connected to a transformer. Each turbine generator has one single-flow high-pressure cylinder, one double-flow intermediate-pressure cylinder and two double-flow low-pressure cylinders. Steam exhausted from the high-pressure cylinder is reheated in the steam generator. Several steam extractions from the turbines preheat feed water in low- and high-pressure heat exchangers and one spray-type open deaerating heat exchanger. The low-pressure turbines exhaust to the condenser.
c) *Condensers*: Cooling water condenses the steam exhausted from the turbines.
d) *Preheating Heat Exchangers and Pumps*: The temperature and pressure of the condensed steam are increased in a series of pumps and heat exchangers.

3.2. Results of Exergy and Energy Analyses

Energy and exergy analyses of the station have been performed [19,21]. Overall balances of exergy and energy for the station are illustrated in Fig. 2. The main findings, which improve understanding of the thermodynamic behaviour of the plant and help identify areas having significant efficiency-improvement potential, follow:

- For the overall plant, the energy efficiency (ratio of net electrical energy output to coal energy input), was found to be 37%, and the corresponding exergy efficiency 36%.
- In the steam generators, the energy and exergy efficiencies were evaluated, considering the increase in energy or exergy of the water as the product. The steam generators appear significantly more efficient on an energy basis (95%) than on an exergy basis (50%). Physically, this discrepancy implies that, although most of the input energy is transferred to the preheated water, the energy is degraded as it is transferred. Most of the exergy losses in the steam generators are associated with internal consumptions (mainly due to combustion and heat transfer).
- In the condensers, a large quantity of energy enters (about 775 MW for each unit), of which close to 100% is rejected; and a small quantity of exergy enters (about 54 MW for each unit), of which about 25% is rejected and 75% internally consumed.
- In other plant devices, energy losses were found to be very small (about 10 MW total), and exergy losses were found to be moderately small (about 150 MW total). The exergy losses are almost completely associated with internal consumptions.

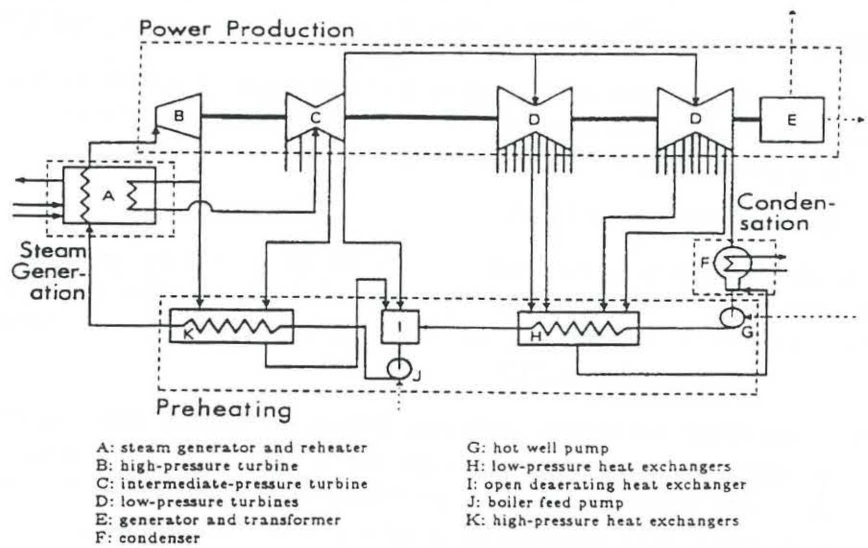

Figure 1. Breakdown of the electrical generating station unit considered into four main sections. The external inputs are coal and air, and the output is stack gas and solid waste for unit A. The external outputs for unit E are electricity and waste heat. Electricity is input to units G and J, and cooling water enters and exits unit F.

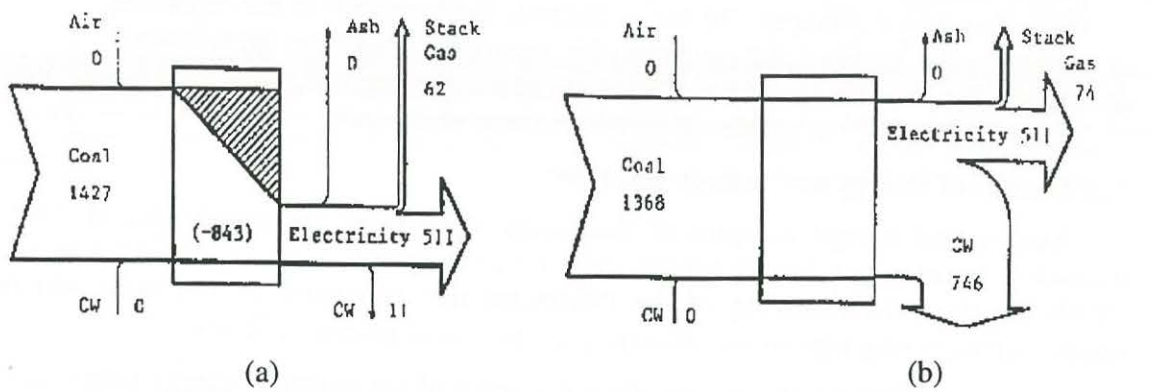

Figure 2. Overall energy and exergy balances for the station. The rectangle in the center of each diagram represents the station. Widths of flow lines are proportional to the relative magnitudes of the represented quantities. CW denotes cooling water. a) Exergy balance showing flow rates (positive values) and consumption rate (negative value, denoted by hatched region) of exergy (in MW). b) Energy balance showing flow rates of energy (in MW).

4. ENVIRONMENTAL IMPLICATIONS OF EXERGY

4.1. Energy Use and Environmental Impact

Energy resources can be used to satisfy human needs and improve quality of life, but generally lead to environment impacts. For instance, the United Nations [3] indicates that effective atmosphere-protection strategies must address the energy sector by increasing efficiency and shifting to environmentally benign energy systems. It was reported that a major efficiency program would provide an important means of reducing CO_2 emissions, and that such activities should be accompanied by measures to reduce the fossil fuel component of the energy mix and to develop alternative energy sources. Increased efficiency also reduces the need for new facilities for the production, transportation, transformation and distribution of energy, and the associated environmental impact of these additional facilities.

Measures to increase energy efficiency can reduce environmental impact by reducing energy losses. Within the scope of exergy methods, as discussed in the next section, such activities lead to increased exergy efficiency and reduced exergy losses (both waste exergy emissions and internal exergy consumptions).

4.2. Thermodynamics and the Environment

People have long been intrigued by the implications of the laws of thermodynamics on the environment. One myth speaks of Ouroboros, a serpent-like creature which survived and regenerated itself by eating only its own tail. By neither taking from nor adding to its environment, this creature was said to be completely environmentally benign and self-sufficient. It is useful to examine this creature in light of the thermodynamic principles recognized today. Assuming that Ouroboros was an isolated system (i.e., it received no energy from the sun or the environment, and emitted no energy during any process), Ouroboros' existence would have violated neither the conservation law for mass nor the first law of thermodynamics (which states energy is conserved). However, unless it was a reversible creature, Ouroboros' existence would have violated the second law (which states that exergy is reduced for all real processes), since Ouroboros would have had to obtain exergy externally to regenerate the tail it ate into an equally ordered part of its body (or it would ultimately have dissipated itself to an unordered lump of mass). Thus, Ouroboros would have to have had an impact on its environment.

Besides demonstrating that, within the limits imposed by the laws of thermodynamics, all real processes must have some impact on the environment, this example is intended to illustrate the following key point: the second law is instrumental in providing insights into environmental impact. Today, the principles demonstrated through this example remain relevant, and technologies are sought having Ouroboros' characteristics of being environmentally benign and self-sufficient (e.g., University of Minnesota researchers built an "energy-conserving" house called Ouroboros [22]). The importance of the second law in understanding environmental impact implies that exergy, which is based on the second law, has an important role to play in this field.

4.3. Exergy and the Environment

The most appropriate link between the second law of thermodynamics and environmental impact has been suggested to be exergy, in part because it is a measure of the departure of the state of a system from that of the environment [8,9]. The magnitude of the exergy of a system depends on the states of both the system and the environment. This departure is zero only when the system is in equilibrium with its environment.

An understanding of the relations between exergy and the environment may reveal the underlying fundamental patterns and forces affecting changes in the environment, and help researchers to deal better with environmental damage. In fact, Tribus and McIrvine [23] suggest that performing exergy analyses of the natural processes occurring on the earth could form a foundation for ecologically sound planning because it would indicate the disturbance caused by large-scale changes. Three relationships between exergy and environmental impact are now discussed, which have been introduced previously [19]. The decrease in the environmental impact of a process, in terms of these measures, as the process exergy efficiency increases is illustrated approximately in Fig. 3.

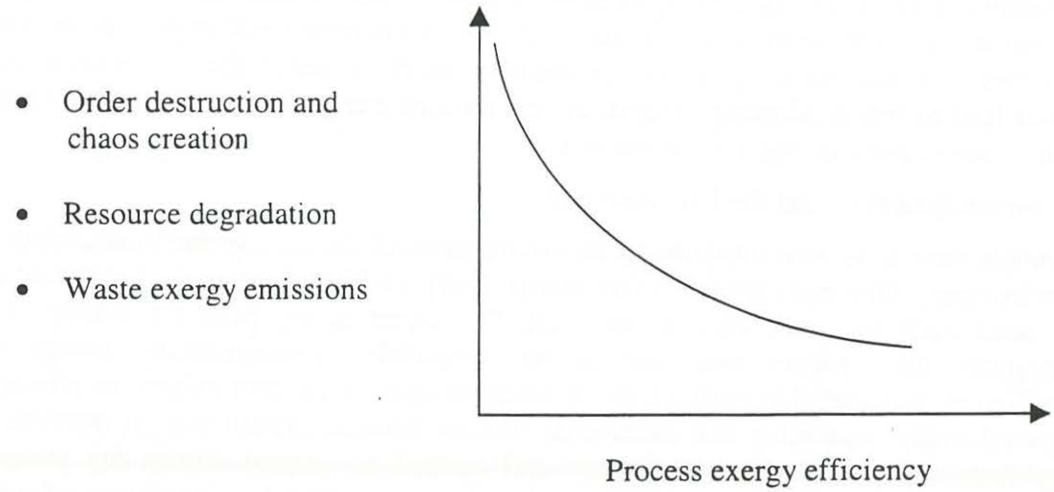

Figure 3. Qualitative illustration of the relation between the exergy efficiency of a process and the associated environmental impact in terms of order destruction and chaos creation, or resource degradation, or waste exergy emissions.

Order destruction and chaos creation. The destruction of order, or the creation of chaos, is a form of environmental damage. Entropy is fundamentally a measure of chaos, and exergy of order. A system of high entropy is more chaotic or disordered than one of low entropy, and relative to the same environment, the exergy of an ordered system is greater than that of a chaotic one. For example, a field with papers scattered about has higher entropy and lower exergy than the field with the papers neatly piled. The exergy difference of the two systems is a measure of (i) the exergy (and order) destroyed when the wind scatters the stack of papers, and (ii) the minimum work required to convert the chaotic system to the ordered one (i.e., to collect the scattered papers). In reality, more than this minimum work, which only applies if a reversible clean-up process is employed, is required. The observations that people are bothered by a landscape polluted with papers chaotically scattered about, but value the order of a clean field with the papers neatly piled at the side, suggests that, on a more abstract level, ideas relating exergy and order in the environment may involve human values [1] and that human values may in part be based on exergy and order.

Resource degradation. The degradation of resources found in nature is a form of environmental damage. Kestin [24] defines a resource as a material, found in nature or created artificially, which is in a state of disequilibrium with the environment, and notes that resources have exergy as a consequence of this disequilibrium. Two main characteristics of resources are valued:

- composition (e.g., metal ores). Many processes exist to increase the value of such resources by purifying them, which increases their exergy. Note that purification is accomplished at the expense of consuming at least an equivalent amount of exergy elsewhere (e.g., using coal to drive metal ore refining).

- reactivity, i.e., their potential to cause change, or "drive" a process (e.g., as for fuels).

Two principal general approaches exist to reduce the environmental impact associated with resource degradation:

- Increased efficiency. Increased efficiency preserves exergy by reducing the exergy necessary for a process, and therefore reduces environmental damage. Increased efficiency also usually reduces exergy emissions which, as discussed in the next section, also play a role in environmental damage.
- Using external exergy resources (e.g., solar energy). The earth is an open system subject to a net influx of exergy from the sun. It is the exergy (or order states) delivered with solar radiation that is valued; all the energy received from the sun is ultimately radiated out to the universe. Environmental damage can be reduced by taking advantage of the openness of the earth and utilizing solar radiation (instead of degrading resources found in nature). This would not be possible if the earth was a closed system, as it would eventually become more and more degraded or "entropic."

Waste exergy emissions. The exergy associated with waste emissions can be viewed as a potential for environmental damage in that the exergy of the wastes, as a consequence of not being in stable equilibrium with the environment, represents a potential to cause change. When emitted to the environment, this exergy represents a potential to change the environment. Usually, emitted exergy causes a change which is damaging to the environment, such as the deaths of fish and plants in some lakes due to the release of specific substances in stack gases as they react and come to equilibrium with the environment, although in some cases the change may be perceived to be beneficial (e.g., the increased growth rate of fish and plants near the cooling-water outlets from thermal power plants). Further, exergy emissions to the environment can interfere with the net input of exergy via solar radiation to the earth (e.g., emissions of CO_2 and other greenhouse gases from many processes appear to cause changes to the atmospheric CO_2 concentration, affecting the receiving and re-radiating of solar radiation by the earth). The relation of waste exergy emissions to environmental damage has been recognized. By considering the economic value of exergy in fuels, for example, Reistad [11] developed an air-pollution rating that he felt was preferable to the mainly empirical ratings then in use, in which the air-pollution cost for a fuel was estimated as either (i) the cost to remove the pollutant or (ii) the cost to society of the pollution in the form of a tax which should be levied if pollutants are not removed from effluent streams.

Although the previous two points indicate simultaneously that exergy in the environment in the form of resources is of value while exergy in the environment in the form of emissions is harmful due to its potential to cause environmental damage, confusion can be avoided by considering whether or not the exergy is constrained (see Fig. 4). Most resources found in the environment are constrained and are by virtue of their exergy of value, while unconstrained emissions of exergy are free to impact in an uncontrolled manner on the environment. To elaborate further on this point, consider a scenario in which emissions to the environment are constrained (e.g., by separating sulfur from stack gases). This action yields two potential benefits: the potential for environmental damage is restrained from the environment, and the now-constrained emission potentially becomes a valued commodity, i.e., a source of exergy.

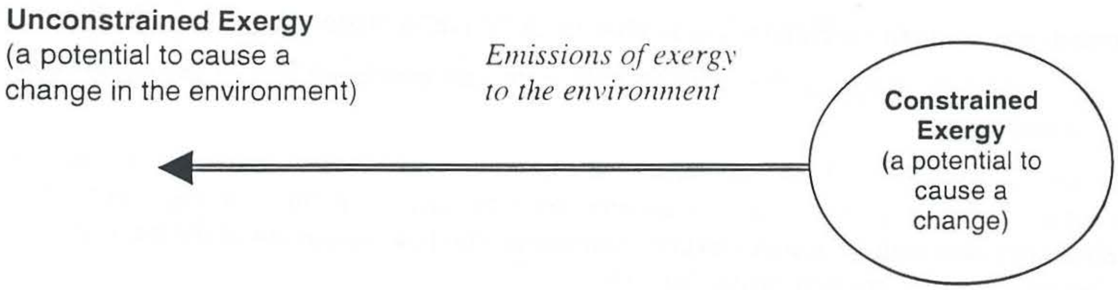

Figure 4. Comparison of constrained and unconstrained exergy illustrating that exergy constrained in a system represents a resource, while exergy emitted to the environment becomes unconstrained and represents a driving potential for environmental damage.

4.4. Exergy and Environmental Sustainability

Sustainable development requires not just that sustainable energy resources be used, but that the resources be used efficiently. Exergy methods are essential in evaluating and improving efficiency. Through efficient utilization, society maximizes the benefits it derives from its resources, while minimizing the negative impacts (such as environmental damage) associated with their use. This implication acknowledges that most energy resources are to some degree finite, so that greater efficiency in utilization allows such resources to contribute to development over a longer period of time. Even if one or more energy resources eventually become inexpensive and widely available, increases in energy efficiency will likely remain sought to reduce the associated environmental impacts and the resource requirements (energy, material, etc.) to create/maintain systems to harvest energy.

Ideally, a society seeking sustainable development utilizes only energy resources which cause no environmental impact. Such a condition can be attained or nearly attained by using energy resources in ways that cause little or no wastes to be emitted into the environment, or that produce only waste emissions having no or minimal negative impact on the environment. This latter condition is usually met when relatively inert emissions that do not react in the environment are released, or when the waste emissions are in or nearly in equilibrium (thermal, mechanical and chemical) with the environment, i.e., when the waste exergy emissions are minimal.

In reality, however, all resource use leads to some degree of environmental impact. A direct relation exists between exergy efficiency (and sometimes energy efficiency) and environmental impact, in that through increased efficiency, a fixed level of services can be satisfied with less energy resources and, in most instances, reduced levels of related waste emissions. Therefore, it follows that the limitations imposed on sustainable development by environmental emissions and their negative impacts can be in part overcome through increased efficiency.

The author and others feel that exergy methods can be used to improve sustainability. Cornelissen [14], for example, points out that one important element in obtaining sustainable development is the use of exergy analysis. By noting that energy can never be "lost" as it is conserved according to the first law of thermodynamics, while exergy can be lost due to internal irreversibilities, the study suggests that exergy losses, particularly due to the use of non-renewable energy forms, should be minimized to obtain sustainable development. Further, the study shows that environmental effects associated with emissions and resource depletion can be expressed in terms of one exergy-based indicator, which is founded on physical principles.

To illustrate better the relation between exergy and sustainability and environmental impact, the diagram in Fig. 3 can be expanded as shown in Fig. 5. There, sustainability is seen to increase and environmental impact to decrease as the exergy efficiency of a process increases. The two limiting efficiency cases are significant:

- As exergy efficiency approaches 100%, environmental impact approaches zero, since exergy is only converted from one form to another without loss (either through internal consumptions or waste emissions). Also sustainability approaches infinity because the process approaches reversibility.
- As exergy efficiency approaches 0%, sustainability approaches zero because exergy-containing resources are used but nothing is accomplished. Also, environmental impact approaches infinity because, to provide a fixed service, an ever increasing quantity of resources must be used and a correspondingly increasing amount of exergy-containing wastes are emitted.

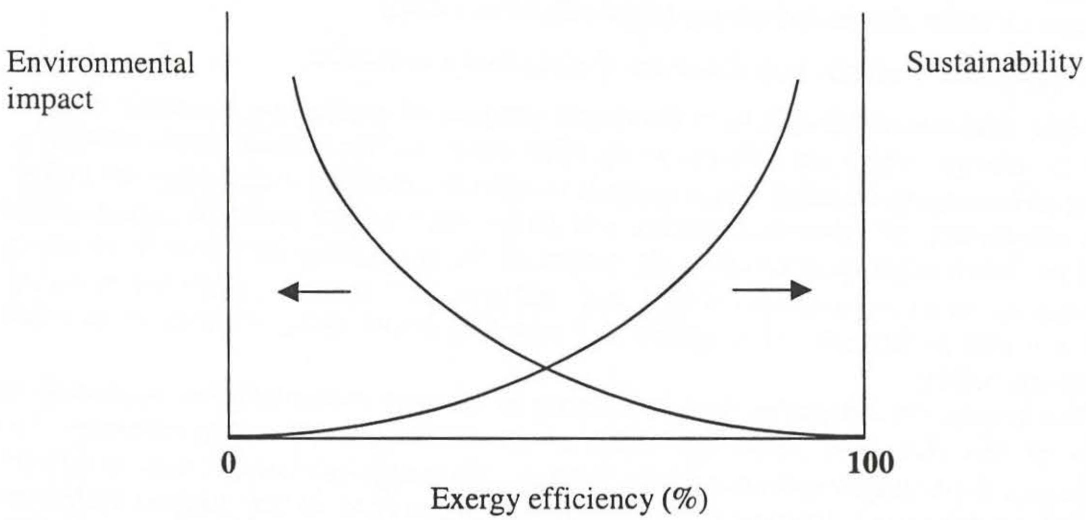

Figure 5. Qualitative illustration of the relation between the environmental impact and sustainability of a process, and its exergy efficiency.

4.5. Implications Regarding Exergy and the Environment: Illustration Revisted

The relationships between exergy and environment described in Section 4.3 are illustrated by revisiting the coal-fired electrical generating station considered in Section 3.

- Waste exergy is emitted from the plant with waste stack gas, solid combustor wastes, and the waste heat released to the atmosphere and the lake from which condenser cooling water is obtained. The exergy of these emissions represents a potential to impact on the environment. Societial concern already exists regarding emissions of harmful chemical constituents in stack gases and thermal pollution in local water bodies of water, but the exergy-based insights into environmental-impact potential of these phenomena is not yet well understood or recognized.

- Coal, a finite resource, is degraded as it drives the electricity generation process. Although a degree of resource degradation can not be avoided for any real process, increased exergy efficiency can reduce the amount of degradation, for the same services or products. In the extreme, if the process in our example were made thermodynamically ideal by increasing the exergy efficiency from 37% to 100%, coal use and the related emissions would each decrease by over 60%.
- Order destruction occurs during the exergy consuming conversion of coal to less ordered stack gases and solid wastes, and chaos creation occurs as wastes are emitted to the environment, allowing the products of combustion to move and interact without constraints throughout the environment.

5. ECONOMIC IMPLICATIONS OF EXERGY

In the analysis and design of energy systems, techniques are often used which combine scientific disciplines (especially thermodynamics) with economics to achieve optimum designs. Economic issues are also important in the evaluation of environmental and greenhouse gas, as well as energy technologies. For energy-conversion devices, costs are conventionally based on energy. Many researchers [21, 25-28], however, have recommended that costs are better distributed among outputs based on exergy.

5.1. Assessment Methods that Combine Exergy and Economics

Many researchers [25-28] have developed methods of performing economic analyses based on exergy, which are referred to by such names as thermoeconomics, second-law costing and exergoeconomics. These analysis techniques recognize that exergy, not energy, is the commodity of value in a system, and assign costs and/or prices to exergy-related variables. These techniques usually help determine the appropriate allocation of economic resources so as to optimize the design and operation of a system, and/or the economic feasibility and profitability of a system (by obtaining actual costs of products and their appropriate prices).

Tsatsaronis [25] identifies four main types of analysis methodologies, depending on which of the following forms the basis of the technique: (i) exergy-economic cost accounting, (ii) exergy-economic calculus analysis, (iii) exergy-economic similarity number, and (iv) product/cost efficiency diagrams. General discussions of the analysis techniques appear in several text books [e.g., 4,5,7,8]. Also, several detailed reviews of these analysis techniques, which include discussions, comparisons and critiques of the different techniques, have recently been published [e.g., 25,26].

5.2. Exergy and Economics: Illustration Revisited

One rationale for the statement that costs are better distributed among outputs if cost accounting is based on exergy is that exergy often is a consistent measure of economic value (i.e., a large quantity of exergy is often associated with a valuable commodity) while energy is only sometimes a consistent measure of economic value.

By way of illustration, it is pointed out that the author has examined the relations between thermodynamic losses and capital costs for devices in the coal-fired electrical generating station considered in Section 3, and suggested possible generalizations in the relation between thermodynamic losses and capital costs [21]. That work examined thermodynamic and economic data for mature devices, and showed that correlations exist between capital costs and thermodynamic losses for devices. The existence of such correlations likely implies that designers knowingly or unknowingly incorporate the recommendations of exergy analysis into process designs indirectly. The results of the analysis of the relations between thermodynamic losses and capital costs for devices in a modern coal-fired electrical generating station led to several preliminary conclusions, which have yet to be generalized to other technologies:

- For the thermodynamic losses considered (energy and exergy loss), a significant parameter appears to be the ratio of thermodynamic loss rate to capital cost.
- A systematic correlation appears to exist between exergy loss rate and capital cost, but not between energy loss rate and capital cost. This finding is based on the observation that the variation in thermodynamic-loss-rate-to-capital-cost ratio values for different devices is large when based on energy loss, and small when based on exergy loss.
- Devices in modern coal-fired electrical generating stations appear to conform approximately to a particular value of the thermodynamic-loss-rate-to-capital-cost ratio (based on exergy loss), which reflects the "appropriate" trade-off between exergy losses and capital costs that is practised in successful plant designs.

6. CONCLUSIONS

This work has demonstrated the benefits of using the principles of thermodynamics via exergy to evaluate energy systems and greenhouse gas technologies. It is concluded that thermodynamics, particularly the concepts encompassing exergy, has a significant role to play in evaluating energy and greenhouse gas technologies. Exergy should prove useful in such activities to engineers and scientists, as well as decision and policy makers. To better define the role of exergy, particularly in the area of environmental impact, further research is needed.

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REFERENCES

1. W. Hafele, *Energy in a Finite World: A Global Systems Analysis*, Ballinger, Toronto (1981).
2. J. Goldemberg, T.B. Johansson, A.K.N. Reddy and R.H. Williams, *Energy for a Sustainable World*, Wiley, New York (1988).
3. M.F. Strong, Energy, environment and development, *Energy Policy* 20, 490-494 (1992).
4. M.J. Moran, *Availability Analysis: A Guide to Efficient Energy Use*, Revised Ed. ASME, N.Y. (1989).
5. T.J. Kotas, *The Exergy Method of Thermal Plant Analysis*, Reprint Ed., Krieger, Malabar, Florida (1995).
6. M.J. Moran and E. Sciubba, Exergy analysis: principles and practice, *J. Engineering for Gas Turbines and Power* 116, 285-290 (1994).
7. J. Szargut, D.R. Morris and F.R. Steward, *Exergy Analysis of Thermal, Chemical and Metallurgical Processes*, Hemisphere, New York (1988).
8. J. Szargut, International progress in second law analysis, *Energy* 5, 709-718 (1980).
9. R.H. Edgerton, *Available Energy and Environmental Economics*, D.C. Heath, Toronto (1992).

10. W.J. Wepfer and R.A. Gaggioli, Reference datums for available energy. In *Thermodynamics: Second Law Analysis*, ed. R.A. Gaggioli, ACS Symp. Ser. 122, Washington, DC, 77-92 (1980).
11. G.M. Reistad, *Availability: Concepts and Applications*, Ph.D. diss., Univ. of Wisconsin, Madison (1970).
12. E. Sciubba, Exergy as a direct measure of environmental impact, *Proc. ASME Advanced Energy Systems Division*, ed. S.M. Aceves *et al.*, AES-Vol. 39, 573-581 (1999).
13. R.U. Ayres, L.W. Ayres and K. Martinas, Exergy, waste accounting, and life-cycle analysis, *Energy* 23, 355-363 (1998).
14. R.L. Cornelissen, *Thermodyanmics and Sustainable Development*, Ph.D. Thesis, University of Twente, the Netherlands (1997).
15. L. Connelly and C.P. Koshland, Two aspects of consumption: using an exergy-based measure of degradation to advance the theory and implementation of industrial ecology, *Resources, Conservation and Recycling* 19, 199-217 (1997).
16. J.C. Creyts and V.P. Carey, Use of extended exergy analysis as a tool for assessment of the environmental impact of industrial processes, *Proc. ASME Advanced Energy Systems Division*, ed. M.L. Ramalingam, ASME, New York, AES-Vol. 37, 129-137 (1997).
17. M. Zhang and G.M. Reistad, Analysis of energy conversion systems, including material and global warming aspects, *Int. J. Heating, Ventilating, Air-Cond. and Refrigerating Research* 1 45-65 (1998).
18. P. Crane, D.S. Scott and M.A. Rosen, Comparison of exergy of emissions from two energy conversion technologies, considering potential for environmental impact, *Int. J. Hydrog. Energy* 17, 345-350 (1992).
19. M.A. Rosen and I. Dincer, On exergy and environmental impact, *Int. J. Energy Res.* 21, 643-654 (1997).
20. M.A. Rosen and I. Dincer, Exergy analysis of waste emissions, *Int. J Energy Res.* 23, 1153-1163 (1999).
21. M.A. Rosen, The relation between thermodynamic losses and capital costs for a modern coal-fired electrical generating station, In *Computer-Aided Energy-Systems Analysis*, ed. G. Tsatsaronis *et al.*, ASME, New York, AES-Vol. 21, 69-78 (1990).
22. S.J. Markovich, Autonomous living in Ouroboros house. In Solar Handbook, *Popular Sci.*, 46-48 (1978).
23. M. Tribus and E.C. McIrivne, Energy and information, *Sci. Am.* 225(3), 179-188 (1971).
24. J. Kestin, Availability: the concept and associated terminology, *Energy* 5, 679-692 (1980).
25. G. Tsatsaronis, A review of exergoeconomic methodologies. In *Second Law Analysis of Thermal Systems*, ed. M.J. Moran and E. Sciubba, ASME, New York, 81-87 (1987).
26. Y.M. El-Sayed and R.A. Gaggioli, A critical review of second law costing methods: parts I and II, *ASME J. Energy Resources Technology* 111, 1-15 (1989).
27. C. Torres, L. Serra, A. Valero and M.A. Lozano, The productive structure and thermoeconomic theories of system optimization, *Proc. ASME Advanced Energy Systems Division*, ed. A.B. Duncan *et al.*, ASME, New York, AES-Vol. 36, 429-436 (1996).
28. G. Tsatsaronis (Ed.), Invited papers on exergoeconomics, *Energy-The Int. Journal* 19, 279-381 (1994).