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Role of exergy in increasing efficiency and sustainability and reducing environmental impact

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Abstract

The use of exergy is described as a measure for identifying and explaining the benefits of sustainable energy and technologies, so the benefits can be clearly understood and appreciated by experts and non-experts alike, and the utilization of sustainable energy and technologies can be increased. Exergy can be used to assess and improve energy systems, and can help better understand the benefits of utilizing green energy by providing more useful and meaningful information than energy provides. Exergy clearly identifies efficiency improvements and reductions in thermodynamic losses attributable to more sustainable technologies. A new sustainability index is developed as a measure of how exergy efficiency affects sustainable development. Exergy can also identify better than energy the environmental benefits and economics of energy technologies. The results suggest that exergy should be utilized by engineers and scientists, as well as decision and policy makers, involved in green energy and technologies in tandem with other objectives and constraints.

Keywords: Exergy; Environment; Sustainability

1. Introduction

To increase the utilization of more environmentally benign and sustainable energy and technologies, the benefits that they bring must be clearly understood and appreciated by experts and non-experts alike. The latter category includes the public, the media and decision makers in industry and government.

The use of energy as a measure for identifying and measuring the benefits of energy systems can be misleading and confusing. Thus, when energy analysis is used to assess the benefits of green energy and technologies, confusion and inaccuracies can result that can hinder their acceptance.

The thermodynamic quantity exergy, which can be used to assess and improve energy systems, can help better understand the benefits of utilizing green energy by providing more useful and meaningful information than energy provides. Exergy clearly identifies efficiency improvements and reductions in thermodynamic losses attributable to green technologies. Exergy can also identify better than energy the environmental benefits and economics of energy technologies. Thus, exergy has an important role to play in increasing utilization of green energy and technologies.

The difference between energy and exergy analysis may be explained considering an example. Consider a geothermal power plant using geothermal liquid water at 160 °C at a rate of 440 kg/s as the heat source, and producing 15 MW of net power in an environment at 25 °C. Energy analysis allows us to determine that this source has an energy value of 251 MW and the energy efficiency of the plant is 6% (15/251 MW). Exergy analysis shows that the source has a work potential (i.e., exergy) of 44.5 MW and the plant exergy efficiency is 34% (15/44.5 MW). Here, the exergy of geothermal water constitutes only 18% of its energy. The remaining 82% is not available for conversion to

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electricity, even with a reversible heat engine. Only 34% of the exergy entering the plant is converted to electricity and the remaining 66% is lost. An exergy analysis of this plant also identifies the sites of exergy losses in a quantitative manner and helps in prioritizing improvement efforts. Clearly, these insights to the plant operation cannot be attained by an energy analysis alone. The low value of energy efficiency here is misleading as the maximum energy efficiency of this plant is limited by its Carnot efficiency whose value in this case is $0.31 = (1\text{–}298\,\text{K}/433\,\text{K})$.

In geothermal power plants, the used geothermal water typically leaves the plant at a temperature much greater than the environment temperature and is reinjected back to the ground. The quality (i.e., exergy) of this reinjected water is much lower than the quality of the same amount of water at 160 °C. An energy balance on the overall power plant shows that input and output energies are equal, while exergy analysis shows that energy quality (i.e., exergy) is degraded in the processes and, in fact, 66% of input exergy is lost including the exergy of reinjected water.

This article discusses the advantages of exergy with the objective of demonstrating how exergy can help improve understanding of green energy and technologies and thus help increase their utilization. The article is intended to help improve understanding and appreciation of exergy analysis by engineers and scientists as well as by industry, the public, the media and government. These groups all must have such understanding if appropriate decisions about green energy and technologies are to be made. This is particularly true of government policy, which can be critical for the introduction of green energy and technologies.

It is noted at the outset that decisions regarding the design and modification of energy systems normally do not consider efficiency as an objective itself. Focusing on only efficiency usually leads to impractical results. Rather, decision makers are usually concerned with maximizing profits while meeting applicable emissions standards and other requirements. But increasing efficiency is often an important way to reduce costs, resource use and environmental emissions.

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, as well as sustainable development. Finally, the ties between exergy and economics, which are important given the interrelations between technical, environmental and economic issues, are described.

2. Background

The relationship between energy and economics, particularly the trade-offs that normally occur between efficiency and costs, has been an important concern for decades. More recently, the environmental impacts of energy use, such as global climate change, ozone depletion and acid rain, have received increasing attention (Hafele, 1981; Goldemberg et al., 1988; Strong, 1992). Concerns have also been expressed in relation to energy about the non-sustainable nature of human activities, and effort has been expended on developing methods for achieving sustainable development. These topics are often related, since the environmental emissions can be reduced by increasing efficiency, and increasing efficiency also increases sustainability by lengthening the lives of resources.

Many suggest that the impact of energy use on the environment and the achievement of increased resource-utilization efficiency, and the economics of energy systems, are best addressed by considering exergy (Moran, 1989; Kotas, 1995; Moran and Sciubba, 1994; Szargut et al., 1988; Szargut, 1980; Edgerton, 1992). Consequently, many methodologies based on exergy have been developed, e.g., exergy analysis for improving the efficiency of energy systems and exergoeconomics for improving the economics of energy systems. The exergy of an energy form or a substance is a measure of its usefulness or quality, and thus is a measure of its potential to cause change. Exergy may be, or provide the basis for, an effective measure of the potential of a substance or energy form to impact the environment (e.g., Edgerton, 1992; Wepfer and Gaggioli, 1980; Reistad, 1970; Sciubba, 1999; Ayres et al., 1998; Cornelissen, 1997; Connelly and Koshland, 1997; Creyts and Carey, 1997; Zhang and Reistad, 1998; Crane et al., 1992; Rosen and Dincer, 1997, 1999, 2003; Tyagi et al., 2005).

In practice, the authors feel 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.

3. Exergy and exergy analysis

Exergy is a measure of the usefulness or value or quality of an energy form. Technically, exergy is defined using thermodynamics principles 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 (Moran, 1989; Kotas, 1995; Moran and Sciubba, 1994; Szargut et al., 1988; Szargut, 1980; Edgerton, 1992). Exergy is a measure of the potential of the system or flow to cause change, as a consequence of not being completely in equilibrium relative to the reference environment. Unlike energy, exergy is not subject to a conservation law (except for ideal processes). Rather exergy is consumed or destroyed, due to non-idealities or irreversibilities in any real process. The exergy consumption during a process is proportional to the entropy created due to irreversibilities associated with the process.

Exergy analysis (Moran, 1989; Kotas, 1995; Moran and Sciubba, 1994; Szargut et al., 1988; Szargut, 1980; Edgerton, 1992) is a methodology that uses the conservation of energy principle (embodied in the first law of thermodynamics) together with non-conservation of entropy principle (embodied in the second law) 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.

Exergy analysis permits many of the shortcomings of energy analysis to be overcome. Exergy analysis is useful in identifying the causes, locations and magnitudes of process inefficiencies. Exergy analysis acknowledges that, although energy cannot be created or destroyed, it can be degraded in quality, eventually reaching a state in which it is in complete equilibrium with the surroundings and hence of no further use for performing tasks. The benefits of exergy analysis clearly go well beyond what many perceive to be the main application of the second law of thermodynamics, which forms the basis of exergy methods. Many feel that the second law simply indicates whether a process is possible or not. Although the second law can do that, it also can indicate the theoretical upper limit for efficiency, which is attained thermodynamically when a process is reversible, as well as how far a real process deviates from that ideality. It is this use of the second law, made most straightforward and understandable via exergy methods, that perhaps is its most valuable application. This application does not just indicate what is not possible, but also indicates where inefficiencies are occurring, and their nature and cause. With this information, targeted appropriate efforts to reduce inefficiencies can be made. Thus, exergy analysis allows for improvements not necessarily attainable via energy methods, like increased efficiency, reduced fuel use and environmental emissions, and cost savings.

In exergy analysis, the characteristics of the reference environment must be specified. 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 leads to some of the implications regarding environmental impact that are discussed subsequently.

Many engineers and scientists suggest that energy systems are best evaluated using exergy analysis because it provides more insights, especially for efficiency improvement, than energy analysis. Exergy analysis and its application to many processes and systems are discussed further elsewhere (Moran, 1989; Kotas, 1995; Moran and Sciubba, 1994; Szargut et al., 1988; Szargut, 1980; Edgerton, 1992).

Many examples can be used to demonstrate the application and benefits of exergy. Some brief ones are presented here for illustrative purposes.

3.1. *Thermal energy storage*

Consider a buried thermal energy storage tank. A hot medium flows through a heat exchanger within the storage and heat is transferred into the storage. After a period of time, a cold fluid is run through the heat exchanger and heat is transferred from the storage into the cold fluid. The amount of heat thus recovered depends on how much heat has escaped from the storage into the surrounding soil, and how long the recovery fluid is passed through the heat exchanger. But a problem arises in evaluating the energy efficiency of this storage because the energy efficiency can be increased simply by lengthening the time that the recovery fluid is circulated. What is neglected here is the fact that the temperature at which the heat is recovered is continually decreasing towards the ambient soil temperature as the fluid circulates. Thus, although the energy recovered increases as the recovery fluid continues to circulate, the exergy recovered hardly increases at all after a certain time, reflecting the fact that recovering heat at near-environmental temperatures does not make storage more efficient thermodynamically.

3.2. *Space heaters*

Space heating can be accomplished in many ways. For an electrical resistance space heater, almost all of the electricity that enters the unit is dissipated to heat within the space. Thus, the energy efficiency is nearly 100% and there are almost no energy losses. Yet, the exergy efficiency of such a device is typically less than 10%, indicating that the same space heating can in theory be achieved using one-tenth of the electricity. In reality, some of these maximum savings in electricity use can be attained using a heat pump. The use of even a relatively inefficient heat pump can reduce the electricity used to achieve the same space heating by one-third. Clearly, the use of energy efficiencies and losses is quite misleading for electrical heating.

The exergy efficiency of a space heater can be shown by considering an example of a room at 25 °C heated by a 2-kW electric resistance heater when the outdoors are at 2 °C. This heater has an energy efficiency of nearly 100% since the electricity consumed is almost entirely converted to useful heat output through electrical resistance. This 2-kW heat rate may be supplied to the room by a reversible heat pump, which requires only 0.144 kW of work input for the same indoor and outdoor temperatures. The exergy efficiency of the heater, defined as the minimum work requirement divided by the actual work input, is 7.2%.

3.3. Ideal heat engine

Consider a Carnot (ideal) heat engine operating between a heat source at a temperature of 600 K in an environment at 300 K. The energy efficiency of this device is 50% (i.e., $1-300/600\,\mathrm{K} = 0.5$). Yet a Carnot engine is ideal. Clearly, the energy efficiency is misleading as it indicates that a significant margin for improvement exists when in fact there is none. The exergy efficiency of this device is 100%, properly indicating its ideal nature in a straightforward and clear manner.

3.4. Actual power plant

Consider electricity generation using an actual power plant. Here, we consider the coal-fired Nanticoke generating station, which has been operating since 1981 in Ontario, Canada. Each of the eight units in the station has a net output of 505 MWe. A single unit of the electrical generating station is illustrated in Fig. 1, and consists of four main sections (Rosen and Dincer, 1997, 1999, 2003):

- *Steam generators*: Pulverized-coal-fired natural circulation steam generators combust coal to produce primary and reheat steam. The flue gas exits the plant via multi-flued chimneys.
- *Turbine generators and transformers*: Steam 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 closed heat exchangers and one spray-type open deaerating heat exchanger.
- *Condensers*: The low-pressure turbines exhaust to the condenser, where cooling water condenses the steam.
- *Preheating heat exchangers and pumps*: The temperature and pressure of the condensed steam are increased in a series of pumps and heat exchangers.

Overall balances of exergy and energy for the station are illustrated in Fig. 2. The main findings (Rosen and Dincer, 2003), which improve understanding of the plant thermodynamic behaviour and identify areas of significant efficiency-improvement potential, follow:

- The overall energy efficiency (ratio of net electrical energy output to coal energy input) was found to be 37%, and the corresponding exergy efficiency 36%.
- 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).
- Large quantities of energy enter the condensers (about 775 MW per unit), of which close to 100% is rejected. A small quantity of exergy enters (about 54 MW per unit), of which about 25% is rejected and 75% internally consumed.
- Energy losses in other plant devices 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.

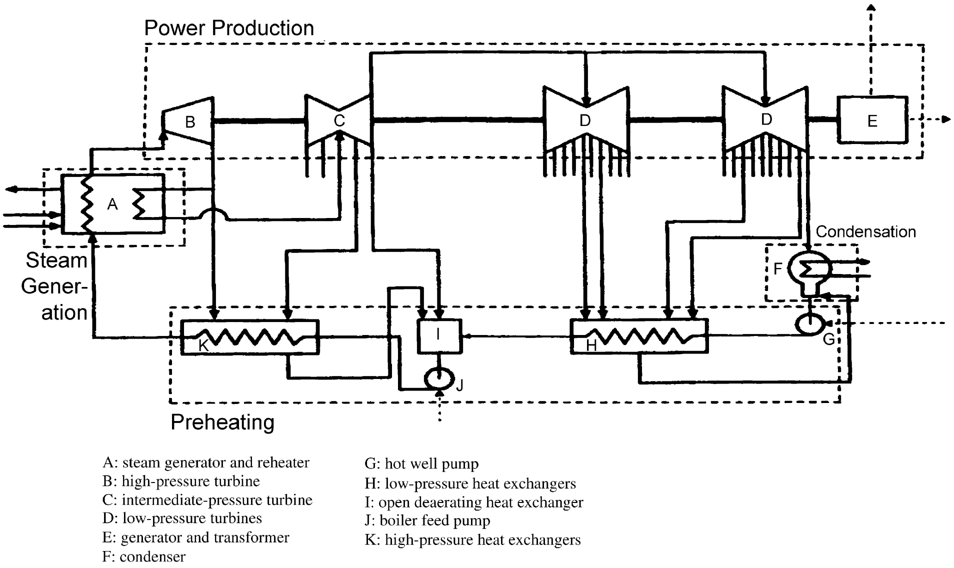

Fig. 1. Breakdown of the electrical generating station unit considered into four main sections. The external inputs are coal and air, and the output is stack gas and solid waste for unit A. The external outputs for unit E are electricity and waste heat. Electricity is input to units G and J, and cooling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

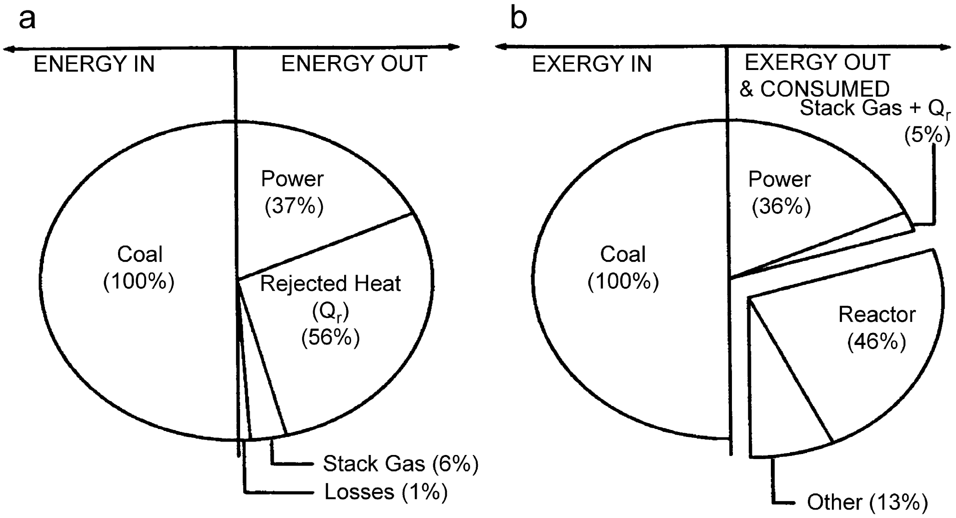

Fig. 2. Overall energy and exergy balances for the station. (a) Energy balance showing inputs and outputs of energy. (b) Exergy balance showing inputs and outputs and consumptions of exergy.

4. Exergy, environment and sustainability

Energy resources can be used to satisfy human needs and improve quality of life, but generally lead to environmental impacts. For instance, the United Nations (Strong, 1992) indicates that effective atmosphere-protection strategies must address the energy sector by increasing efficiency and shifting to environmentally benign energy systems. Reduced CO_2 emissions can be achieved via increased efficiency, reductions in the fossil fuel component of the energy mix and the introduction of alternative energy sources.

4.1. Exergy and the environment

Measures to increase energy efficiency can reduce environmental impact by reducing energy losses. Within the scope of exergy methods, such activities lead to increased exergy efficiency and reduced exergy losses (both waste exergy emissions and internal exergy consumptions). But there are additional ways by which exergy can help understand and reduce environmental impact.

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 (Szargut, 1980; Edgerton, 1992). 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.

The relations between exergy and the environment may reveal the underlying fundamental patterns and forces affecting environmental changes, and help researchers deal better with environmental damage. In fact, Tribus and McIrvine (1971) suggest exergy analyses of the natural processes occurring on the earth could form a basis for ecologically sound planning because it would indicate the disturbance caused by large-scale changes.

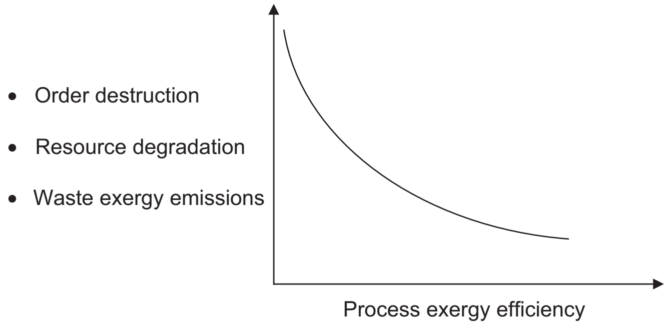

Fig. 3. Qualitative illustration of the relation between the exergy efficiency of a process and the associated environmental impact in terms of order destruction, or resource degradation, or waste exergy emissions.

Three relationships between exergy and environmental impact, introduced previously (Rosen and Dincer, 1997), are now discussed. The decrease in the environmental impact of a process, in terms of these measures, as process exergy efficiency increases is illustrated approximately in Fig. 3. It is noted that Fig. 3 is generally applicable to many processes, but not to all. In particular, when efficiency is reduced through the introduction of a pollution-control measure the environmental impact may decrease even as the efficiency decreases.

4.1.1. Order destruction

The destruction of order is a form of environmental damage. Entropy is fundamentally a measure of disorder and exergy of order. A system of high entropy is more 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 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 (Hafele, 1981) and that human values may in part be based on exergy and order.

4.1.2. *Resource degradation*

The degradation of resources found in nature is a form of environmental damage. Kestin (1980) 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: reactivity (a resource's potential to fuel a process) and composition. Processes exist to increase the value (and exergy) of 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). Two 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 plays 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."

4.1.3. *Waste exergy emissions*

Since the exergy of wastes, as a consequence of not being in stable equilibrium with the environment, represents a potential to cause change, the exergy associated with waste emissions can be viewed as a potential for environmental damage. When emitted to the environment, this exergy represents a potential to change the environment. Usually, emitted exergy causes a change that 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). By considering the economic value of exergy in fuels, Reistad (1970) 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. Reistad suggested that the latter cost be in the form of a tax which would 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. Note that unconstrained exergy is not always harmful, but poses the potential to cause harm. Also, constrained exergy is always valuable, although the value depends on economic factors. To elaborate further on this point, consider a scenario in which emissions to the environment are constrained (e.g., by separating sulphur 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.

4.2. *Illustration*

The relationships between exergy and environment are illustrated by revisiting the coal-fired electrical generating station considered earlier.

- Waste exergy is emitted from the plant with stack gas, solid combustor wastes and the waste heat released to the atmosphere and the lake. The exergy of these emissions represents a potential to impact on the environment. Societal 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 the

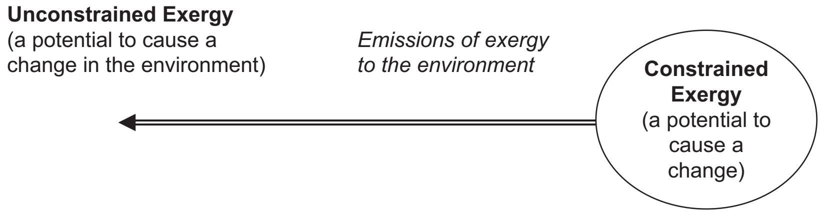

Fig. 4. Comparison of constrained and unconstrained exergy. Exergy constrained in a system represents a resource, while exergy emitted to the environment is an unconstrained driving potential for environmental damage.

environmental-impact potential of these phenomena are 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 cannot 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%. Realistic increases in efficiency would achieve part of this reduction in coal use and emissions. It is noted here that exergy does not explicitly indicate how to achieve an efficiency increase, but rather points out the potential that exists for increased efficiency. Exergy analysis does provide indications of where efficiency gains can be found in a plant, and what is causing losses. With this knowledge, the creativity of engineers and scientists can be used to determine ways to take advantage of the potential to increase efficiency.
- 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. Here, order is based on thermodynamic constructs in which work is required in theory to be input to recreate the original substance, i.e., to re-organize the system.

4.3. *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 improving efficiency, which allows society to maximize the benefits it derives from its resources while minimizing the negative impacts (such as environmental damage). 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, increased efficiency will likely remain desired. This is because increased efficiency reduces environmental impacts and 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, and limitations imposed on sustainable development by environmental emissions can be in part overcome through increased efficiency.

Exergy methods can be used to improve sustainability. Cornelissen (1997), 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. Cornelissen also shows that environmental effects associated with emissions and resource depletion can be expressed in terms of one exergy-based indicator, founded on physical principles.

Fig. 3 can be expanded to illustrate how sustainability increases and environmental impact decreases as the exergy efficiency of a process increases (see Fig. 5). 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), and 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, and 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. As with Fig. 3, it is pointed

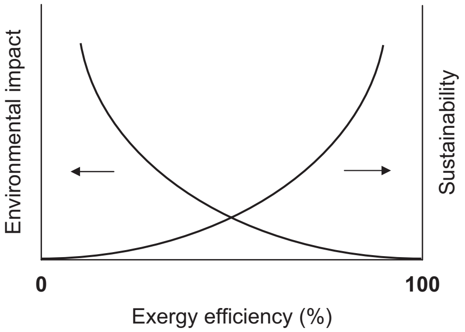

Fig. 5. Qualitative illustration of the relation between the environmental impact and sustainability of a process, and its exergy efficiency.

out that Fig. 5 is not universally applicable, for instance when an energy-consuming pollution-control measure is introduced.

The relationships between environmental impact and sustainability versus exergy efficiency may be expressed quantitatively by some examples. But first we develop the formulation needed for such an analysis. The exergy efficiency of a power plant may be expressed as

$$\psi_{\mathrm{PP}} = \frac{W_{\mathrm{out}}}{Ex_{\mathrm{in}}}, \tag{1}$$

where W_{out} is the net work produced and Ex_{in} is the exergy input, which is equal to the mass of fuel consumed times the specific fuel exergy. The exergy efficiency of a refrigeration cycle is expressible as the actual coefficient of performance (COP) divided by the reversible COP for the same temperature limits:

$$\psi_{\mathrm{RC}} = \frac{COP_{\mathrm{act}}}{COP_{\mathrm{rev}}}. \tag{2}$$

The reversible COP is defined in terms of low-temperature reservoir (T_{L}) and high-temperature reservoir (T_{H}) as

$$COP_{\mathrm{rev}} = \frac{T_{\mathrm{L}}}{T_{\mathrm{H}} - T_{\mathrm{L}}}. \tag{3}$$

Connelly and Koshland (1997) suggest that the efficiency of fossil fuel consumption be characterized by a depletion number defined as

$$D_{\mathrm{p}} = \frac{Ex_{\mathrm{D}}}{Ex_{\mathrm{in}}}, \tag{4}$$

which represents the relationship between the exergy destruction (Ex_{D}) and the exergy input (Ex_{in}) by fuel consumption. The relationship between the depletion factor and the exergy efficiency is

$$\psi = 1 - D_{\mathrm{p}}. \tag{5}$$

Now, we express the sustainability of the fuel resource by a sustainability index (SI) as the inverse of the depletion number:

$$SI = \frac{1}{D_{\mathrm{p}}}. \tag{6}$$

As a first example, we consider a power plant using natural gas (approximated as methane) as the fuel. We express the environmental impact in terms of the amount of carbon dioxide emission. A balanced chemical combustion equation of methane shows that for each kilogram of methane burned, 2.75 kg of carbon dioxide (CO_2) is released. The specific chemical exergy of methane is 51,840 kJ/kg (Szargut et al., 1988). The amount of carbon dioxide emitted and the sustainability index as a function of the exergy efficiency for 1 kWh of power production are plotted in Fig. 6.

As a second example, we consider an air-conditioner used to maintain a space at 25 °C (298 K) when the outdoors are at 35 °C (308 K). It is assumed that the electricity consumed by this air-conditioner is produced in a coal-fired power plant. Based on a report by USDOE (1998), for 1 kW of electricity produced in a coal-fired power plant, 6.38 g of SO_2 and 3.69 g of NO_x are emitted. In this example, we express the environmental impact in terms of the total SO_2 and NO_x emissions. These emissions and the sustainability index as a function of the exergy efficiency for 1 kWh of cooling load from the space are also illustrated in Fig. 6. The trends explained in Fig. 5 generally apply to the results shown in Fig. 6.

The relationships between environmental impact and sustainability versus exergy efficiency shown in Figs. 5 and 6 directly apply to energy systems consuming non-free energy resources like fossil fuels. However, let us consider a geothermal power plant with an exergy efficiency of 20%. Even though the exergy efficiency of the plant is rather low it does not have a low sustainability index or a high environmental impact since the plant uses a renewable energy source. But we should remember that this geother-

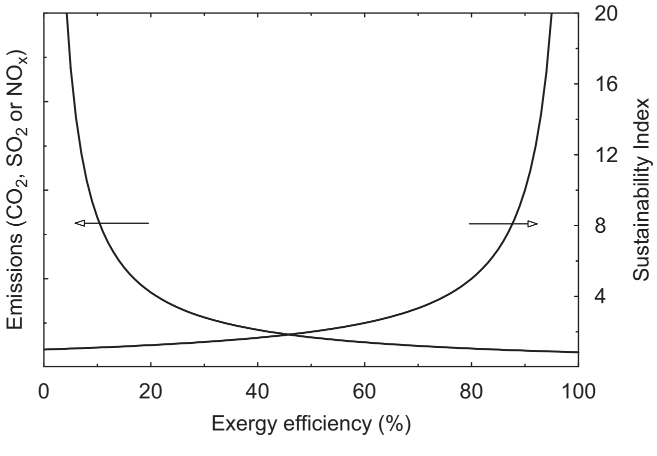

Fig. 6. Quantitative illustration of the relation between the CO_2, SO_2 or NO_x emissions and sustainability index (SI) of a process, and its exergy efficiency. CO_2 emission is calculated for power generation where the fuel is methane and the results are for 1 kWh of power output. SO_2 and NO_x emissions are calculated for an air-conditioner with electricity as the work input and the results are for 1 kWh of cooling load. The absolute values represented by the emissions axis are not shown. At an exergy efficiency of 50%, the CO_2 emission is 0.38 kg while the SO_2 emission is 0.43 kg and the NO_x emission is 0.25 g.

mal power plant still contributes to sustainability and reduces environmental emissions since its existence prevents the consumption of fossil fuels and associated environmental effects. If the exergy efficiency of this plant is increased from 20% to 25% as a result of modifications, its contribution to sustainability and environmental stewardship will also increase since more fossil fuel use is offset. We can conclude that the relationships between environmental impact and sustainability versus exergy efficiency indirectly apply to energy systems using renewable energy sources. The contributions of energy systems using renewable resources are quantified even more comprehensively when the full life cycle of the systems is considered, including energy use and emissions associated with creating the devices.

5. Exergy and economics

In the analysis and design of energy systems, technical disciplines (especially thermodynamics) are combined with economics to achieve optimum designs. Economic issues are important in the evaluation of green energy technologies. For energy-conversion devices, costs are conventionally based on energy. Many researchers (Rosen and Dincer, 2003; Tsatsaronis, 1987, 1994; El-Sayed and Gaggioli, 1989; Mazur, 2005), however, have recommended that costs are better distributed among outputs based on exergy.

Methods have developed of performing economic analyses based on exergy, which are referred to as thermoeconomics, second-law costing and exergoeconomics (Tsatsaronis, 1987, 1994; El-Sayed and Gaggioli, 1989; Mazur, 2005; Jaber et al., 2004). These methods recognize that exergy, not energy, is the commodity of value in a system, and assign costs and/or prices to exergy-related variables. These methods 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 (1987) 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. These methods are discussed and compared elsewhere (e.g., Moran, 1989; Kotas, 1995; Szargut et al., 1988; Szargut, 1980; Tsatsaronis, 1987; El-Sayed and Gaggioli, 1989).

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. This rationale can be illustrated with results of previous research by the authors on the coal-fired electrical generating station considered earlier, which suggested possible general relations between thermodynamic losses and capital costs (Rosen and Dincer, 2003). 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 observations:

- 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

The benefits of using exergy to evaluate efficiency, environmental impact and sustainability have been demonstrated. It is concluded that the concepts encompassing exergy have a significant role to play in evaluating and increasing the use of sustainable energy and technologies. Although decisions regarding the design and modification of energy systems are normally concerned not just with efficiency but also with economics, environmental impact, safety and other issues, exergy should prove useful in design and improvement activities to engineers and scientists, as well as decision and policy makers.

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