Rethinking exergy efficiency in favor of exergy sustainability as a criteria for design

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Abstract

Engineering design in power generation or conversion has typically focused on minimizing exergy losses (entropy gains), or maximizing economic returns. Both entropy minimization and profit maximization are readily obtainable and acceptable objective criteria for design of thermodynamic processes. However, sustainability concerns are not addressed by efficient or economy alone. Previous research presented a framework for considering minimal environmental impact as an alternative design criterion for minimizing the pollution potential of exergetic wastes. This paper proposes a mathematical model for maximizing resource renewability. A life-cycle metric describing the replacement time frame of the primary exergy source is presented. When coupled, the two metrics together partially assess the overall sustainability of the design.

Introduction

It is now widely accepted among policy makers in Europe and the United States that the traditional mode of environmental regulation that has dominated the past several decades has been successful at reducing point-source pollutant loadings but will nonetheless be insufficient to move highly developed nations towards environmental *sustainability.* Consequently, regulatory agencies such as the USEPA are increasingly thinking in terms of the entire material life-cycle – including resource extraction, benefaction, processing and manufacture and end-of-life – rather than simply regulating waste disposal (USEPA 2003). Unfortunately, promulgation of life-cycle regulations to foster sustainability remains a difficult challenge for policy-makers, partly because environmental science and policy research has yet to establish operational measures of sustainability that can be employed to benchmark progress or guide policy decisions. As a result, sustainability initiatives in most major international industries have been voluntary and guided by heuristic rules of thumb such as improving material and energy efficiency or advancing a social or ethical agenda (e.g. anti-sweatshop practices).

Sustainability remains an elusive concept partly because it has so many dimensions (Seager and Theis 2002a). However, the *thermodynamic* dimension – i.e., that which deals with material and energy resources -- is nearly universally recognized as an essential aspect of almost any sustainability discussion. Several authors have discussed operational definitions of sustainability based upon the thermodynamic concept of *exergy* (e.g., Wall and Gong 2001, Gong and Wall 2001, Lems, van der Kooi and de Swaan Arons 2003, Berthiaume, Bouchard, and Rosen 2001, and Rosen and Dincer 2001). Exergy has also been employed as a quantitative basis for life cycle assessment (e.g., Ayers, Ayers, and Martinás 1998, Hau and Bakshi 2004, Ukidwe and Bakshi 2004) and as a tool for estimating overall environmental impact (Seager and Theis 2002a, Seager and Theis 2002b, Daniel and Rosen 2002). Nonetheless, exergetic studies are more typically concerned with maximizing the economic effort obtainable from a thermodynamic process such as distillation, combined heat and power generation, or others (Brodynasky et al. 1994, Tsatsaronis and Moran 1997, Szargut 2005). To broaden the application of exergy to sustainability studies, some distinctions among different forms and impacts of exergy must be made that are not generally considered relevant for efficiency studies.

For example, not all forms of waste exergy can be considered to impact the environment in the same way. In particular, exergy released to the environment in the form of waste heat may be potentially much less damaging than exergy released in the form of chemical pollution (Seager and Theis 2002a). Similarly, waste noise, light and radiation all have distinctly different environmental or ecological effects. Although each of these exergetic forms may be lumped together as “waste” from the traditional standpoint of efficiency maximization (i.e., entropy generation minimization), they should be analyzed separately for the purpose of studying deleterious effects on the environment. Similarly, it is also important to differentiate among different exergy *sources*. The most common approach is to characterize the environmental ramifications of any exergy source by a life-cycle accounting of the wastes generated at each stage of the production chain (as well as emissions generated during use). However, this approach essentially ignores the importance of assessing sustainability from a conservation standpoint. That is, it fails to ascertain whether the resource can be regenerated or how long the resources are expected to last at the present rate of consumption. Consequently, the renewability of a primary exergy source is an important characteristic that should inform a thermodynamic sustainability analysis.

One particular area where sustainability concerns are often mentioned is in the use of “nonrenewable” fuel sources. There is a general consensus is that if we are going to continue using combustion of fuels to meet our energy (exergy) needs we are going to have to employ fuels that can be renewed more rapidly or that may be consumed over a longer time frame without depleting the resource beyond a defined level of acceptable availability. Several approaches to assessing fuel renewability have been proposed. The simplest is a binomial approach that classifies a source as either “renewable” or “non-renewable” (e.g., Berthiaume, Bouchard, and Rosen 2001). A slightly more sophisticated approach is to estimate both the current rate of consumption and available stock of a particular source, and divide the latter by the former to estimate the time over which the present rate of consumption may be ‘sustained.’ Another viewpoint of the problems associated with the burning of fuels could focus on the time required to return the environment to an acceptable composition after the release of fuel emissions. In this case, a metric for quantifying the amount of time required to rehabilitate the environment is required. For example, release of carbon dioxide from fossil fuel combustion may require anywhere between 80 to 200 years to sequester from the atmosphere by natural processes such as photosynthesis. Efforts in these areas have yielded some means of quantifying fuel sustainability, but they have more often led to illogical or incomprehensive results. This research aims at taking the next step toward developing a widely accepted and universally applicable metric for the thermodynamic renewability of a fuel.

A Critique of Existing Renewability Models

Of all the approaches to defining an operational measure of exergy source renewability, the simplest is the binomial classification system of ‘renewable’ or ‘non-renewable.’ Generally, biomass, solar, wind, and hydropower are recognized as renewable, while all other forms (e.g., fossil fuels, nuclear) are considered non-renewable.[1] However, this system is problematic in several ways:

- Biomass resources have different growth or regeneration rates ranging from months to decades (or even centuries).
- Current consumption rates of extremely plentiful resources (e.g., coal, oil sands) might be sustained for dozens of generations without exhaustion, despite being characterized as non-renewable.
- The renewability of mixed-resource streams is very difficult to characterize.

A slightly more sophisticated approach accounting for changes in stocks and flows has been proposed by Lems, van der Kooi and de Swaan Arons (2003). By this method, the ‘renewability indicator’ is defined as the current stock of resource divided by the time rate of depletion of the stock, which results in an estimate of the length of time until the stock is completely exhausted. From the standpoint of strong sustainability, any rate of use that results in depletion of a stock is by definition unsustainable. However, from a weak sustainability standpoint (in which substitution of new resources mitigates the loss of exhausted resources), it may be advantageous to use the cheapest, most plentiful resources first. Consequently, the renewability indiactor approach might be employed in a weak sustainability framework for prioritizing a search for substitutes for those resources closest to exhaustion.

The primary contribution of the renewability indicator method is to introduce the concept of thinking about renewability as a continuum, rather than a binominal variable (Figure 1). Rapidly renewable resources can be found on the left edge of the continuum. For example, wind might be thought of nearly instantaneously renewable. (It is never used up, and with some periodic exceptions is available always). Solar power is renewable on a daily basis. In general terms, hydro power is renewable on a seasonal or annual basis (depending upon the variability of rainy seasons), whereas some biennial crop rotations would suggest a renewability of two years (e.g., corn ethanol and soy biodiesel). The exergy of animal fats (e.g., whale oil) might be renewable on a scale varying from years to decades, whereas timber resources might be renewable over an epoch of decades or centuries. At the right edge of the continuum are those resources that are renewable only over a geologic timeframe -- hundreds of millions of years. However, it may be more accurate to characterize these types of resources by the capacity of the environment to assimilate the wastes generated by their consumption. That is, they may be constrained *at the end of the pipe*, rather than the beginning. For example, it may take between 80 and 200 years to absorb the carbon dioxide generated by fossil fuels combustion. Alternatively, it may require tens of thousands of years for radioactive wastes to decay to background levels.

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[1] Geothermal power presents an interesting challenge to this classification system that is worthy of further discussion. On the one hand, the ultimate source of geothermal exergy is as old as the earth itself, and on a grand scale the idea of ‘renewability’ can only be defined on the basis of underlying cosmological assumptions. However, on a smaller scale geothermal reserves can be recognized as existing in isolation from one another. The only meaningful sources are those that are at very shallow depths (relative to the thickness of the earth’s crust), and these are constantly regenerating in active volcanic areas.

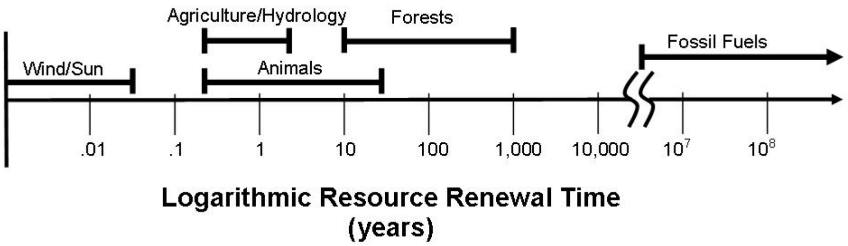

Figure 1: Renewability Continuum Timeline

Nonetheless, the renewability indicator approach is mathematically insufficient. In the case of resources that are extremely rapidly renewable (such as wind or solar power), no valid mathematical description of 'stocks' – or even rate of change in stocks – is possible. Thus, the renewability indicator as proposed will only be adequate for resources that have finite and measurable amounts of storage and rates of depletion -- such as those resources that are typically defined as non-renewable, or at least are renewable over long enough time frames to allow accumulation of stocks that are easy to preserve (such as forests). Moreover, this method is apparently only appropriate for the consumption of a single resource or for multiple resources that are perfect thermodynamic substitutes (weak sustainability). It is unclear how this approach is helpful if only imperfect substitutes are discovered, or how the renewability of mixed-resource streams might be characterized.

Towards a Comprehensive Renewability Metric

To improve upon the renewability indicator approach, it is necessary to develop a metric that is independent of the idea of 'stocks' and allows for combination of multiple resource streams into a single indicator. A new metric, termed resource renewal time (t_r) and may be calculated as follows:

$$1 = \frac{t_r}{t_1} + \sum_{i=1}^{n} \frac{t_r - t_i}{t_i \gamma_{i-1}} \qquad (1)$$

where:

t_r = resource renewal time

t_1 = renewal times for resource 1

n = total number of resources considered

t_i = renewal time for resource i

$\gamma_{\text{i-1}}$ = substitutability of resource i for resource 1

The first term in equation (1) represents the fraction of renewal time used to restore resource 1 as defined in terms of Figure 1. In this case, 'resources' can be defined as either materials or energy extracted from the environment or ecosystem services related to the assimilation of wastes, depending upon the problem of interest. The subsequent terms represent the fraction of renewal time used to restore each of the remaining resources. The substitutability factor allows for combination of resources that are completely substitutable (as in extremely weak sustainability) or only marginally substitutable, as defined in economic, thermodynamic, or other terms. For example, substitutability could be defined on a life-cycle basis that relates the amount of a substitute primary resource required to generate an equivalent economic activity (e.g., corn ethanol versus petroleum for load-miles driven), or it may be determined on an economic basis based upon price ratios. Accordingly, the substitutability indicator is always positive (or zero), where one represents perfect substitutability. A substitutability less than one indicates that the second resource is not of the same quality (for a given economic purpose), whereas substitutability of greater than one indicates that the second resource is of higher quality. Solving equation (1) for the resource renewal time of a combination of two sources as a function of substitutability gives the following result, represented in Figure 2:

$$t_r = \frac{t_1 t_2 (\gamma_{2-1} + 1)}{t_1 \gamma_{2-1} + t_2} \qquad (2)$$

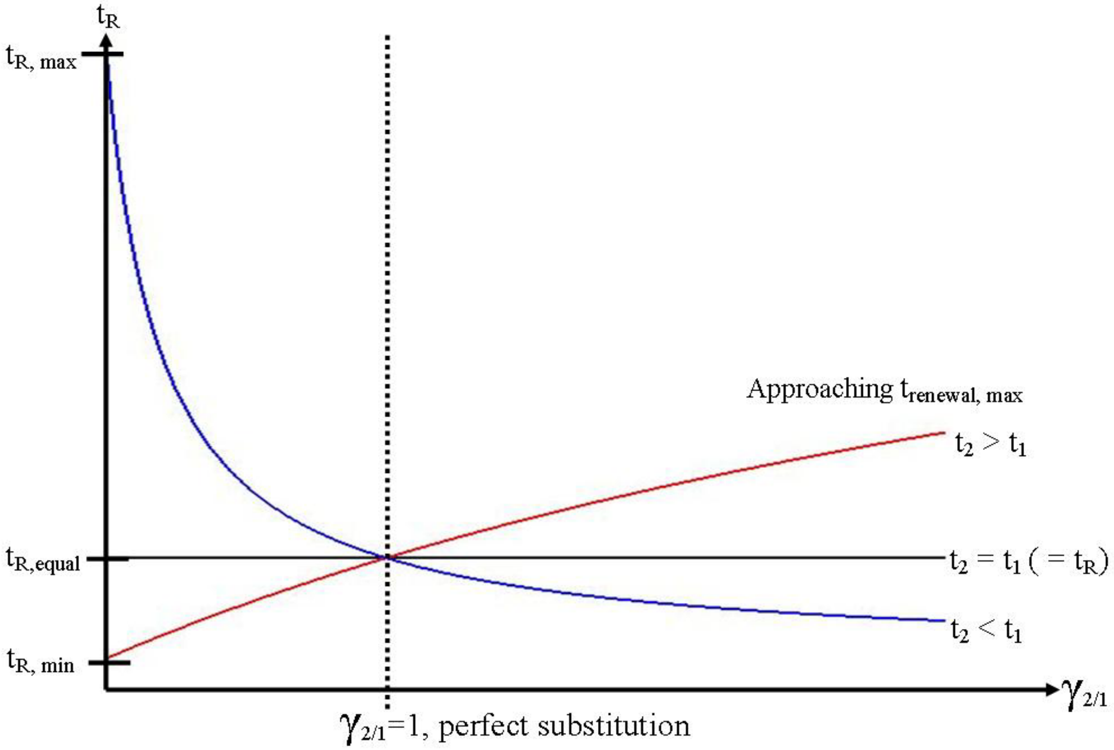

Figure 2: The effects on total renewal time for a mixture of two substances of varying substitutablities ($\gamma_{2/1}$).

Description of an Analogous Problem: Two Painters

An excellent analogy for the use of the mixed-resource model is a problem that might be encountered in a high school algebra class:

Painter A can paint an entire house in 3 hours, but Painter B takes 5 hours to paint the same house. How long will it take both painters working simultaneously to paint 2 houses?

This is equivalent to the replacement time idea in that two efforts are being used to complete a task for each effort. At first glance, one might say that the painters can only paint as fast as the slowest painter, so it would take 5*2=10 hours to paint the houses. Then, someone else may realize that Painter A could do the entire work alone in 3*2=6 hours. It then becomes obvious that it must take less than 6 hours for both painters working simultaneously. Since the underlying assumption here is that each painter can do the work equally well, γ=1. Plugging the numbers into the model, we get:

$$t_{tot} = \frac{(1+\gamma)t_A t_B}{\gamma t_A + t_B} = \frac{2*3*5}{3+5} = \frac{30}{8} = 3\,{}^{3}\!/_{4}\ hours$$

Now, let's make the problem more interesting. Let's say that Painter A is painting the same house as before, but that Painter B is painting a Victorian house that requires a lot of precision work and climbing up and down ladders. Painter B can still finish the Victorian house in 5 hours, but Painter A is highly frustrated by the slow work and ladder climbing. To account for this, we will assume that Painter A is only 1/3 as effective as Painter B at painting the Victorian house, which means that $\gamma_{A-B} = 3$. Plugging this into the model gives:

$$t_{tot} = \frac{(1+\gamma_{A-B})t_A t_B}{t_A \gamma_{A-B} + t_B} = \frac{4*3*5}{3*3+5} = \frac{60}{14} = 4\,{}^{2}\!/_{7}\ hours$$

This result makes sense logically. A substitutability of 3 for Painter A on the Victorian house means he is less effective and that it would actually take him 9 hours to paint that house entirely on his own. Since he is less effective when he begins helping painter B on the Victorian house, it will take the pair longer to complete the whole job.

The analogous problem in resource renewability might be represented at the gas pump, where both regular and E10 (10% ethanol) gas are available. A consumer interested in making the more renewable (i.e., more sustainable, all else being equal) choice might be interested to know how the substitution of fuel derived from corn for gasoline from petroleum changes the renewability of the fuel. The combined resource renewal time of the fuel mix may be greater than or less than that of the petroleum-derived gasoline, depending upon the exergetic life-cycle characteristics of the supply chain.

Conclusions and Future Work

All material or energetic process can be characterized as thermodynamic processes. When the motivation of the analysis is principally a characterization of environmental or sustainability aspects, the thermodynamic concept of exergy is the appropriate framework. Moreover, exergy is applicable on a life-cycle basis to determine both the total thermodynamic resources required to support an economic activity and the ultimate fate of that exergy in the environment (or overall thermodynamic efficiency). However, when considering sustainability it is not sufficient to aggregate all exergetic sources and sinks into an overall assessment. Different forms of waste exergy have different qualitative and quantitative environmental and ecological effects. Similarly, the time to replace or renew consumed primary exergy sources is highly variable, as is the time required for the environment to assimilate exergetic wastes. Consequently, the characterization of the renewability of any primary exergy resource is an important step is assessment of the sustainability of any particular economic activity, and should be of interest to policy makers. However, virtually all economic activity is supported by a mix of primary exergy resources with different substitutabilities and renewal times. Current mathematical models of renewability are either too simplistic or mathematically insufficient. Therefore, this paper proposes a new model based upon the resource renewal time that is independent of resource stocks and capable of characterizing a resource mix of varying substitutability.

Future work will be directed towards application of the model proposed to the problem of bio-based transportation fuels, corn ethanol and soy biodiesel in particular, as substitutes for petroleum-based resources. While it has long been argued that current crop production rates are insufficient to fully fuel American transportation needs – even if all agricultural production were shifted to transportation fuels – it has not yet been determined whether substitution of a portion of fuel mix with bio-based fuels as an intermediary step would improve renewability measures or not. Presentation of a transportation-based case study is expected to illustrate the concept sufficiently to assess the intellectual utility of extending application to solar, hydro, geothermal and other alternative energy technologies. When combined with the concept of pollution potential of exergetic wastes, the renewability metric is expected to create a more complete assessment of the thermodynamic sustainability of any process on a life-cycle basis.

References

USEPA 2003. *2003-2008 EPA Strategic Plan: Direction for the Future.* USEPA: Washington DC.

Ayres, Robert U., Leslie W. Ayres, and Katalin Martinás. Exergy, waste accounting, and life-cycle analysis. Energy. 23 (5) (1998) 355-363.

Berthiaume, Richard, Christian Bouchard, and Marc A. Rosen. Exergetic evaluation of the renewability of a biofuel. Exergy Int. J. 1 (4) (2001) 256–268.

Hua, Jorge L. and Bhavik Bakshi. 2004. Expanding exergy analysis to account for ecosystem products and services. *Environmental Science and Technology.* 38:3768-3777.

Ukidwe, Nandanu and Bhavik Bakshi. 2004. Thermodynamic accounting of ecosystem contribution to economic sectors with application to 1992 U.S. economy. *Envrionmental Science and Technology.* 38:4810-4827.

Brodyanski, V.M., M.V. Sorin, and P. LeGeoff. The efficiency of industrial process: Exergy analysis and optimization. London, UK: Elsevier, 1994.

Daniel, Jason J. and Marc A. Rosen. Exergetic environmental assessment of life cycle emissions for various automobiles and fuels. Exergy Int. J. 2 (2002) 283-294.

Gong, Mei and Göran Wall. On exergy and sustainable development—Part 2: Indicators and methods. Exergy Int. J. 1 (4) (2001) 217–233.

Lems, S., H.J. van der Kooi, and J. de Swaan Arons. Quantifying technological aspects of process sustainability: a thermodynamic approach. Clean Techn Environ Policy 5 (2003) 248–253.

Rosen, Marc A. and Ibrahim Dincer. Exergy as the confluence of energy, environment and sustainable development. Exergy Int. J. 1 (1) (2001) 3-13.

Seager, Thomas P. and Thomas L. Thies. A uniform definition and quantitative basis for industrial ecology. Journal of Cleaner Production. 10 (2002a) 225-235.

Seager, Thomas P. and Thomas L. Thies. Exergetic pollution potential: Estimating the revocability of chemical pollution. Exergy Int. J. 2 (2002b) 273-282.

Szargut, Jan. Exergy Method: Technical and Ecological Applications. Southampton, UK: WIT, 2005.

Tsatsaronis, G and M.J. Moran. Exergy-aided cost minimization. Energy Conversion and Management. 38 (15) (1997) 1535-1542.

Wall, Göran, and Mei Gong. On exergy and sustainable development—Part 1: Conditions and concepts. Exergy Int. J. 1 (3) (2001) 128–145.