WORKING PAPER SERIES

2006/02

AN ECONOMIC ASSESSMENT OF SOLAR PV SYSTEMS

Jim Airola and David Bergeron

Energy payback time is a common metric when evaluating the feasibility of PV system installations. We survey recent published estimates of energy payback time and contrast those estimates with traditional cost analyses. We provide a critical review of the method of "energy payback time" and suggest explanations for the divergence between energy payback and more conventional measures of financial payback. We argue that energy payback time analysis undercounts the true energy costs of installed PV systems.

Defense Resources Management Institute
School of International Graduate Studies
Naval Postgraduate School
Building 234
699 Dyer Road
Monterey, CA 93943-5138
831-656-2306
www.nps.navy.mil/drmi

The views herein expressed reflect the views of the author and are not the policy of DRMI, the Naval Postgraduate School, or the U.S. Government.

Defense Resources Management Institute
Naval Postgraduate School

The Defense Resources Management Institute (DRMI) is an educational institution sponsored and supervised by the Secretary of Defense and located at the Naval Postgraduate School in Monterey, California. Since 1965 the Institute has conducted professional education programs in analytical decision making and resources management for military officers of all services and for senior civilian officials of the United States and 149 other countries.

The mission of the Defense Resources Management Institute is to educate civilian and military government officials in the principles and concepts of defense resources management.

The unique course offerings create an interdisciplinary, interactive learning environment that facilitates the exchange of ideas among U.S. and international participants in Monterey, California, and locations worldwide. These programs are presented on a regularly scheduled basis at DRMI in Monterey and by specific arrangement at other locations in the United States and in other countries.

The success of DRMI reflects the breadth and depth of the in-house technical expertise that DRMI can draw upon. The DRMI Faculty, a community of scholars and practitioners, are experts in defense resources management and has published in major academic and technical journals. The faculty has extensive experience in providing technical assistance and educational programs worldwide over the past 40 years. Our educational strategy is one of collaboration, tailored to the specific environment of the participant.

The Defense Resources Management Institute specializes in four broad educational areas:

- Economic analysis of the public sector
- Operations research of public sector decision problems
- Public budgeting and fiscal management
- Defense organizations and management methods

For more information about our educational and technical assistance activities, please visit our website at **http://www.nps.navy.mil/drmi** or email us at drmiadmin@nps.edu.

AN ECONOMIC ASSESSMENT OF SOLAR PV SYSTEMS

Jim Airola
Assistant Professor of Economics
Naval Postgraduate School
Monterey, CA
jsairola@nps.edu

David Bergeron
President
SunDanzer Development
Tucson, AZ
david@sundanzer.com

ABSTRACT

Energy payback time is a common metric when evaluating the feasibility of PV system installations. We survey recent published estimates of energy payback time and contrast those estimates with traditional cost analyses. We provide a critical review of the method of "energy payback time" and suggest explanations for the divergence between energy payback and more conventional measures of financial payback. We argue that energy payback time analysis undercounts the true energy costs of installed PV systems.

1. INTRODUCTION

A common method of evaluating the feasibility of solar photovoltaic systems is "energy payback time"(EPBT), defined as the time required for a system to produce the energy equal to that consumed in its production. As a thought experiment, EPBT makes a great deal of intuitive sense and is easy to understand and interpret. EPBT is rooted in a long history of similar analyses roughly described as "energy analysis" which strive to measure the economic viability of any energy producing process by whether or not the process produces more, or less, energy than was consumed in its production. But as has always been the case, a large disconnect exists between the measures of EPBT and net benefits calculated through standard financial analysis. This large difference makes us suspicious that either the embodied energy has been undercounted, or the relative contribution of other inputs is overvalued by the manufacturers. This paper explores the reasons why this difference exists and offers a critique of EPBT analysis.

It might strike the casual observer as strange that the profitability of purchasing a PV system would be measured in energy payback time. It is expected that most consumers would care about the point at which the cost savings are greater than the initial outlay and would consider the outlay to be "paid back." As we will see below, the consensus estimates of current EPBT studies is that photovoltaic (PV) systems payback all the energy consumed in their production within about five years. However, at the current market price of the same PV cells and grid-provided electricity, the time required to payback the initial investment (at a 0% discount rate) is often greater than the expected life of the panel. The consumer must ask, why can't I just pay for the energy embodied in the PV cell, and sell the energy that it produces, and experience a cost payback of just five years? As it stands, the consumer must incur real costs to realize real benefits that will not equalize for fifty years, even if future benefits are not discounted.

What explains the relatively large disparity between cost payback time and energy payback time? We propose two major explanations. First of all, most EPBT studies include only a few initial 'rounds' of embodied energy in the inputs. Second, EPBT does not include the energy opportunity costs of non-energy inputs. We conclude by suggesting that the total costs of the inputs are a useful measure for the total resources used in the production of PV electricity, and to the extent that resources can be substituted for one another, are a good measure of the total *energy* used in their production. Our paper proceeds as follows. The first section describes the current emphasis on EPBT or variations in net energy analysis. The second accounts for the difference in conventional cost-benefit analysis and EPBT. We conclude by arguing that any project which is unprofitable is likely to be a net energy loser, that is to say consume more energy in its manufacture and installation than it produces.

2. STUDIES COMPARED

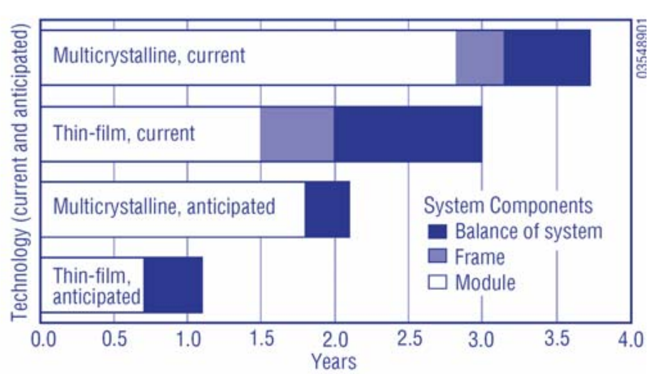
2.1 EPBT Analysis

We consider several recent papers which analyzed the EPBT of individual solar modules and of complete systems. The first paper by Knapp and Jester (6) principally considered the EPBT of single crystalline Silicon (sc-Si) and Copper Indium Diselenide (CIS) technology in production at Shell Solar. This analysis estimated payback times in the range of 3.3 years for the sc-Si and as low as 1.8 years for the CIS. The low rates are optimistic in that they predict higher efficiencies once higher CIS production rates are achieved. These estimates do not include the energy embodied in the Balance of System (BOS) components or other required manufacturing inputs, such as: 1) the energy embodied in the factory equipment, 2) the energy needed to transport goods to and from the factory, 3) energy used by employees commuting to and from work (or total energy embodied in providing labor to the factory), or 4) the energy required for decommissioning and disposal.

A second study, by Alsema, et.al. (1), included EPBT for the modules as well as more detailed EPBT for the BOS components in a few different overall system configurations: grid-connected (battery-free) and off-grid (with battery) as well as different array mounting options and panel technologies. Based on 1997 technology, these more complete systems had an EPBT of 3-9 years. With 3 years being available with thin film or multi-crystalline Silicon (with the low cost ingot silicon available)

A final paper, by Murray and Peterson (4), considers an actual 60kW installation in Ohio. They estimated a 7.3 year payback time but did not include the embodied energy in 1) the PV factory capital cost, 2) transportation related energy needs, 3) energy required to support labor cost in manufacturing or installation, 4) energy associated with decommissioning and disposal.

Based on these and other papers, the National Renewable Energy Lab (NREL) published a PV FAQ sheet with the following summary data:



These summary results are representative of a number of such studies of energy payback time and indicate that most research expects a typical PV installation to produce all the energy that was consumed in its production within five years.

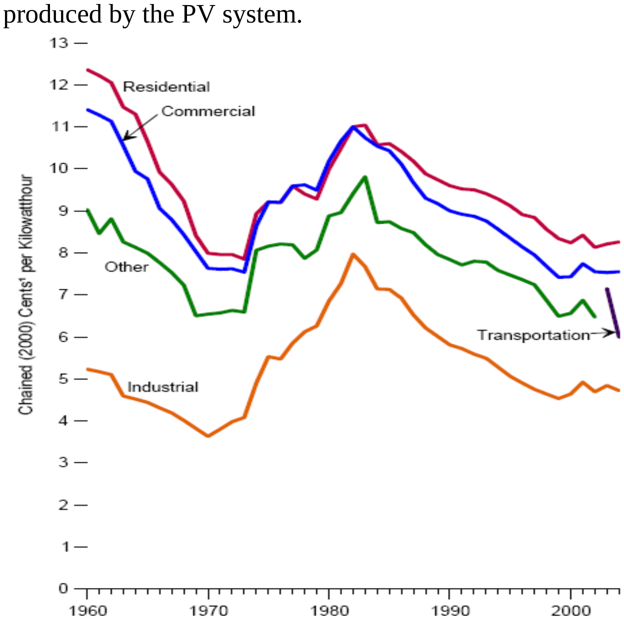
2.2 Financial Analysis

The following is a table of actual quoted turn-key installed cost of grid-tied PV systems in the US. The cost included all materials, labor, and fees associated with a complete installation.

TABLE 1: PV Costs

Location	Rated PV (kW)	Total Cost*	Annual Output (kWh)	Cost/ Watt	Cost/ kWh
California	3.7	$25.7K	6,456	$6.95	$3.98
New Jersey	6.0	$45.0K	6,598	$7.50	$6.83
Arizona	3.06	$23.8K	4,986	$7.77	$4.77
Selected Data					$3.98

The next step in the financial analysis is to estimate the value of the energy produced by the grid-tied PV system. It may not be obvious, but it is useful to price the value of the electricity produced, at the average price that the PV manufacturer and installer actually pays. This puts the financial and EPBT on a level playing field. A survey of 3 US PV manufacturers and typical national residential electric rates (installer's costs) result in a composite electricity cost of $0.08/kWhr. This number was used in the financial payback analysis as the starting value of electricity produced by the PV system.



The financial analysis must also use a discount rate for future cash flows and an escalation rate for the price of electricity. For simplicity, we will assume all values to be in "real" terms (inflation adjusted). Figure 1 illustrates that between 1960 and 2003, the real (inflation adjusted) price of electricity fell. So the payback table is given for several possible escalation scenarios. The California Energy Commission is actually projecting a decrease in electric rates for the next few years. The real discount rate is assumed to be 4%, meaning that one can borrow funds at 4% above the expected inflation rate.

Real Escalation Rate	-4%	-2%	0%	2%	4%
Payback, Yrs	Never	Never	Never	161	50

This finding is also consistent with the Murray and Peterson paper which indicated no financial payback on the 60kW Ohio system. Given that the PV systems will most likely not last 50 years, a financial payback will not occur.

Using the most expected assumptions, the following table summarizes the comparison between the published energy and financial payback periods.

PAYBACK METHOD	PAYBACK TIME
EPBT	3-5 Years
Financial	Never

The balance of this paper addresses the reasons why EPBT and Financial payback do not agree.

3. MEASURING EMBODIED ENERGY

The first possible explanation for the difference in the two measures of payback is that while EPBT studies include the direct energy inputs such as electricity into the factory where the solar panels are made, as well as the energy embodied in the raw materials, many of them only consider a portion of the indirect energy such as the energy embodied in labor, capital, or other materials. Seldom do any studies consider further rounds of embodied energy that may have been involved in the production of the indirect inputs, for example the gasoline required to get the worker to the factory or the energy embodied in the factory itself.
The studies we cite use an approach referred to as process analysis, and is one of at least two ways to estimate the amount of embodied energy in a PV cell. Since most of these studies utilize a process analysis that measures the energy content of inputs such as reading the meters of the PV factory, it is easy to see the impracticality of measuring earlier 'rounds' of embedded energy. In fact, while this bias is recognized, few studies have attempted to estimate its size. An example is Deenapanray, et al(3) who state that "the energy embodied in the materials far exceeds the energy embodied in the production machinery, and the latter can be neglected for practical purposes(i.e. first-order calculations)." But this omission could be large.

Another common approach to measure embodied energy (or any embodied resource[i] for that matter) is known as input-output analysis. Input-output analysis is a top-down approach that uses monetary transactions by sector to account for the complex ways in which industries interconnect[ii]. An obvious first pass at measuring this bias would be to compare these process analysis type studies with input-output studies. Since both methods are used extensively in life-cycle cost analysis, there exists a rich literature which examines the ramifications of utilizing process analysis and the biases which may be incurred. We only present an overview here.

Input-output studies utilize measures of inputs associated with specific output sectors in the aggregate economy. We know of few attempts to estimate EPBT using input-output analysis for the obvious reason that PV production is of such small scale in the overall economy that it cannot be identified as a specific "sector." However, we can at least approximate the size of the bias mentioned above by looking at other, more identifiable, sectors. For example, a recent study of embodied energy in commercial building construction found that process analysis accounted for about 2/3 of the embodied energy estimated using input-output analysis. Other studies illustrate that the system incompleteness (inability to measure energy inputs involved in previous 'rounds' of inputs) inherent in process analysis understates the embodied energy as measured by input-output analysis by a third or more. Lenzen(7) compared process analysis using various rounds to input-output analysis for 132 industries in Australia, finding differences between the two mostly above 50% for first-order calculations (process analysis considering only the first round of inputs) and around 30% for second-order calculations (process analysis considering the first two rounds of inputs).

To illustrate our point, we use input-output tables published by the BEA (1997) to calculate direct and indirect energy use for certain industries. If we define the vector A as the direct inter-industry coefficient matrix and D the vector of direct primary energy consumed per unit of output per sector, the total energy consumed is calculated as $D(I-A)^{-1}$, where I is the identity matrix. It should be noted that process analysis measures energy embodied as simply D, in the case of measuring the first round of energy inputs, or D+DA if including two rounds. The input-output analysis would allow the measure of all rounds. We find that the ratio of direct energy to total energy to be approximately one-third in the manufacturing industry, one-tenth in apparel, and two-thirds in the chemical industry. This corresponds to published studies finding direct energy to total energy ratios of .26 in the housing industry.

Next, if we calculate the ratio of (D+DA)/ total energy, the results change but only slightly. That is, even if the process analysis is able to capture the first two rounds of the energy embodied in the PV cell, it is still likely to underestimate the total embodied energy by a substantial amount. When we include the first three rounds of energy, we find that on average, total embodied energy is underestimated by 20%. We expect this to be a conservative estimate, since few EPBT studies include more than two rounds (and many only one). Thus, we conclude that at least a part of the difference between the financial and energy payback times can be accounted for by the incompleteness of the process analysis boundaries.

4. ENERGY OPPORTUNITY COSTS OF NON-ENERGY INPUTS

The second and more significant explanation for the difference between the payback time as measured by either energy or money is the omission of what we refer to as the energy opportunity costs of non-energy inputs. This is the ability for non-energy inputs, such as labor, capital, and materials to substitute for energy. This issue also has a long tradition in the literature and has been well-developed elsewhere. Here we briefly develop the theory through intuition and example.

Suppose the economy has only two inputs and only two outputs, one of which is manufactured electricity. Let us assume that the two inputs are labor and energy, and the other output is food. Suppose also that food can be produced by either combining large amounts of labor with small amounts of energy (labor-intensive) or by combining small amounts of labor with large amounts of energy(energy-intensive) and that current food manufacturers utilize both methods, depending on their particular cost structure. Imagine in the short-run that energy and labor are held fixed and all labor in our economy is employed. It must be that any additional use of labor in the manufacture of electricity will be offset by a shift in food production from the labor-intensive to the energy-intensive factory and will result in an increase in the use of electricity in the food industry. If the producers of electricity employ additional labor, it must be the case that the food producers will be required to increase their overall use of energy to produce an equivalent amount of food. Thus, even though the labor has no embodied energy per se to include in an EPBT analysis regarding the manufactured electricity, the labor clearly has an opportunity cost which can be measured in units of electricity.

An illustration of the substitution of labor for energy is the case of national policy regarding speed limits on interstate highways. This is clearly a tradeoff between energy (fuel savings) and labor (time savings). If our time had no energy equivalent value, then we could not possibly analyze this trade-off. But our time *can* be measured in energy savings, and we *do* make this tradeoff, either implicitly or explicitly, all the time. In fact, as the value of the fuel savings relative to time savings fell in the 1990's, many states repealed the 55mph speed limits that were enacted during the oil crisis of the 1970's. It follows that in determining the embodied energy contained in PV cells it is necessary to include these energy opportunity costs. That is to say, even if all the direct energy embodied within the labor or capital or material is properly accounted for, we must still add the energy that is being substituted for by those inputs. Within a large, complex economy, these 'opportunity costs' are a real measure of embodied energy in the sense that energy is necessarily consumed elsewhere.

We can think of many examples of labor, capital, or materials substituting for energy. Home insulation, for instance, is a way for labor and materials to combine to save energy. The decision of where to live is often driven by the availability of cheap fuel, and as the cost of fuel has risen in the past decade, individuals have opted for smaller cars or increased preferences for proximate work-space living. Labor is able to substitute for energy in agriculture in pest management services, where experts utilize their knowledge to minimize the use of biocides. And technology, which is essentially embodied labor, substitutes for energy through innovations such as hybrid technologies.

Thus a full accounting of the energy embodied in all the inputs into the manufacture of PV cells and other materials necessary for the balance of systems would include not only the energy embodied in the first round of inputs, but all successive rounds and the energy opportunity costs of the non-energy inputs such as labor, capital, and materials. How is it possible to count all the energy within all of these inputs? We will now suggest a way[iii].

Let us suppose that the manufacturer of PV electricity follows a standard neoclassical production function such that

$$Q = f\left(E, X_1, X_2, \ldots. X_n\right)$$

Where Q represents manufactured energy, E is direct energy input, and the X's refer to all other inputs. Let us assume, for the time being, that the manufacturer breaks even in the sense that the revenue of the sale of energy just equals the sum of the costs of the inputs as follows:

$$P_e Q = P_e E + \sum_n P_i X_i$$

Where, conveniently, we assume the price of the homogeneous energy is the same for both the input *E* and the output *Q*. Taking partial derivatives and dividing through by the common P_e, we arrive at:

$$\partial Q = \partial E + \sum_n \partial X_i \frac{P_i}{P_e}$$

Furthermore, assume that the production function F represents the use of all inputs in the production of all other goods, economy-wide it can be shown that:

$$\frac{P_i}{P_e} = \frac{\partial F / \partial E}{\partial F / \partial X_i}$$

holds for all inputs. That is, the market-clearing relative price of inputs equals the ratio of their marginal products elsewhere in the economy. Substituting, we find that

$$\partial Q = \partial E + \sum_n \partial X_i \frac{\partial F / \partial E}{\partial F / \partial X_i}$$

Or that the energy produced is simply the sum of the direct energy plus the energy opportunity cost of all other inputs. Note that the second term in the equation represents the energy opportunity costs of the non-energy inputs. Thus, at the margin[iv], the concepts are equivalent. If markets were functioning perfectly, and producers were to minimize the cost of producing PV panels, the best measure of the embodied energy would simply be to sum the costs of the inputs!

In a modern, complex economy characterized by scarce resources, the economist's traditional approach has been to measure the relative scarcity of a resource by its market-determined price. The price then acts as a numeraire, and allows us to value labor in terms of capital, capital in terms of materials, or energy in terms of all other resources. Thus, although the opportunity costs of non-energy inputs such as capital and labor are difficult to measure, the use of money prices as a numeraire allows us to value labor in terms of energy, as well as any other input. Therefore, since money prices are much more available, we suggest that a proximate measure of the total energy embodied in a PV installation is simply the money cost of the installation.

5. CONCLUSION

There remain at least two additional explanations for the difference between the energy payback and the financial payback. First, many EPBT studies omit the embodied energy in the battery system or inverter (balance of systems). When a household is considering the cost of a PV system, the total system cost considered includes these peripheral requirements since it is obvious that the PV module is of little use if the customer purchases the panel only to put it in their garage and never use it. Thus to the extent that the EPBT study omits these costs, the difference will be even greater.

Second, if the manufacturers realize economic profits, in the sense that the price they charge for the PV panel greatly exaggerates the sum of the costs of the inputs, the financial payback time would be a poor measure of the true cost of the resources embodied. However, anecdotal evidence suggests that PV manufacturing is a very competitive industry and it is doubtful that industry-wide profits vary much from manufacturing as a whole. It should be noted that if this is the case, any subsidies are likely to be captured by the producers rather than result in increased net energy.

While we have shown that typical studies of EPBT are strongly biased upward for at least two primary reasons, we believe this bias to be the result of methodological shortcomings in the EPBT procedure and not due to any broader over-enthusiasm on the part of the analysts. To the economist, the market-clearing price of a resource is a good measure of the value of energy, labor, or any other resource that is embodied in it. Economic theory asserts that in a well-functioning market, money is a sufficient numeraire useful in the allocation of resources. Although the history of economic thought has often entertained notions of different numeraire goods, such as land(physiocrats), labor(Marx), and energy(technocrats), it is the neoclassical version of subjective value which has survived. From our perspective, it makes little sense to ignore such readily available information as prices in the analysis of solar PV feasibility.

Perhaps we can turn the question on its head and ask the following: What price of oil is required before the financial payback time of a PV installation equals five years? If oil were to cost, say, $200/barrel, we would expect the price of electricity to rise, the real (inflation-adjusted) price of labor to fall, and the financial calculus would be dramatically different. Although many of these price shocks would flow through so that the price of the PV module would rise, we suspect that at some oil price, the financial payback would approach five years, if in fact, the PV module is a net energy producer.

As most are keenly aware, several years ago the direct energy (as measured by process analysis) to manufacture a solar module was greater than the amount of energy the module would produce in its lifetime. But even with this being the case, PV found economically viable applications such as handheld calculators, satellites, small loads in remote locations, etc. In these applications, energy was 'banked' in a solar panel and then used in a location where electricity was not readily or practically available. In a sense, the module served as an energy bank, or more exactly, an energy annuity. A one-time energy investment followed by smaller energy payments over time, and in two different locations. It is still the case that solar electricity has many varied and robust applications that are economically feasible, and those applications should be pursued. But if as has been argued here, and shown elsewhere, financial feasibility is a valid measure for the production of net electricity, net energy stocks will only be enhanced if the public pursues economically feasible systems.

While the indirect energy costs and the energy opportunity costs of non-energy inputs in PV production may be difficult to measure, we argue that the relation between financial feasibility and EPBT are such that the former may be used as a proxy for the latter. In this regard, we find measures of net energy, such as energy payback time, to be suboptimal decision-making criteria for the feasibility of an energy production system, likely leading to suboptimal energy utilization in aggregate.

Thus, it is possible, and likely, that the utilization of energy production processes that are not feasible from a financial viewpoint lead to an allocation of resources such that the total net energy produced is negative, or less than that produced using strictly feasible forms of energy production.

4. REFERENCES

1. Alsema, E., Frankl, P., and Kato, K., Energy Pay-back Time of Photovoltaic Energy Systems: Present Status and Prospects, presented at the 2nd World Conference on Photovoltaic Solar Energy Conversion, Vienna, 6-10 July 1998.
2. Baumol, W. and Wolff, E., Subsidies to New Energy Sources: Do They Add to Energy Stocks?", Journal of Political Economy, 1989, vol 89:5
3. Deenapanray, P., Blakers, A., Weber, K., and Everett, V., Embodied Energy of Sliver Modules, Australian National University
4. Murray, J.E. and Petersen, J.E. "Payback and Currencies of Energy, Carbon Dioxide and Money for a 60 KW Photovoltaic Array", Conference Proceedings of the American Solar Energy Society.
5. Keoleian, G and Lewis, G. Application of Life-cycle Energy Analysis to Photovoltaic Module Design. Progress in Photovoltaics: Research and Applications, Vol 5, 287-300, 1997.
6. Knapp, K.E. and Jester, T.L.," An Empirical Perspective on the Energy Payback Time for Photovoltaic Modules", *Solar 2000 Conference*, Madison, WI.
7. Lenzen, M. "Errors in Conventional and Input-Output-base Life-Cycle Inventories", Journal of Industrial Ecology 4:4 pgs 127-148.
8. NREL *PV FAQs* DOE/GO-102004-1847 January 2004

---

[i] Input-output tables have been used to evaluate embodied land, labor, CO_2,etc.

[ii] So for example, if the total steel industry uses 5 GJ of energy per year and produced 500 million tons of steel, steel contains 3.4 kHr of energy per pound.

[iii] See Baumol and Wolff (2)for a more rigorous treatment

[iv] It is interesting to note that one of the measurement difficulties regarding EPBT is how to count the energy embodied in the silicon feedstock, since the feedstock is essentially rejected material from the micro-electronics industry. A conservative view would include all the embodied energy, another line of reasoning argues for using only a portion of the energy since it is more or less a waste product. However, using the price as a proxy for the embodied energy would be more likely to capture its true energy opportunity cost, in the sense that it more appropriately accounts for the marginal value of the feedstock in the manufacturing process.