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As environmental considerations become more important in policy decisions and planning, a compelling need has emerged for reliable and robust indices of environmental use. This is particularly true when choosing between alternative policies, which requires the identification of variables that can be quantified, that are general enough to allow comparison between quite different sorts of processes, that provide key measures or indices, and that yield true measures of the amount of use of the environment. Towards this end, the quantities derived from thermodynamics are the most obvious and natural, and they meet all of these criteria.

Thermodynamic potential is a fundamental measure of a system's capacity to perform work. The science of thermodynamics enables us to determine the minimum expenditure of thermodynamic potential to achieve a given physical change. Since every process requires the consumption of some thermodynamic potential we are able to compare different processes and select that which is the most thermodynamically efficient. The change in thermodynamic potential associated with a process will measure all of the energy exchanged as well as the effects upon the degree of disorder or dilution, i.e., the entropy of the system.

The two essential forms of stored potential are energy and order. There are multiple forms of energy storage, including hydroelectric facilities, fossil fuels, solar energy, nuclear technologies, etc. Order is used when, for example, we obtain materials from concentrated ore bodies rather than by finding them distributed evenly over the planet's surface. Some forms of stored potential are readily accessible, while others require considerable effort and energy expenditure before they can be used. Measuring the total stored potential can be quite difficult and involves a considerable amount of guesswork. However, it is possible to measure accurately the change in potential associated with different processes, so that the thriftiest process can be identified and adopted.

This approach is different in practice from the money-based "least cost" method of optimizing production, so it is important to stress the differences between economic and thermodynamic analysis. Economic analysis is based upon perceptions of present value and scarcity as expressed in the marketplace, where the supply and demand framework is modeled on an instantaneous evaluation of the popular perception of shortages. However, "one cannot take seriously using a short-term market analysis to decide, say, in the year 2171, whether all the remaining fossil fuel should be reserved for the chemical industry."(9) But if economists were to determine their estimates of shortage by undertaking increasingly long-term analyses, even with discounting, their estimates would come closer and closer to those made by thermodynamicists. In a sufficiently long time frame, it becomes evident that the most important scarcity is of thermodynamic potential; thus thermodynamic analysis becomes essential.

SYSTEM DEFINED

Our system is one in which the manufacture of goods consumes materials and other resources from the environment. To calculate the real thermodynamic cost of a manufactured object, we evaluate the amount of thermodynamic potential that was extracted from the environment to produce the good, and subtract the amount of thermodynamic potential that remains stored in the object. In the unrealizable, idealized thermodynamic limit, the thermodynamic potential that resides in an object is identical to the potential extracted from the environment, the net change in potential is zero, and the process has merely transformed one form of potential into another. This naive ideal can never be reality, however; the net costs are always greater than zero, and there is always a loss of potential both in producing the good and in discarding it. This net loss from production is a true loss as it can not be recovered.

THERMODYNAMIC ESTIMATES

As an example of this thermodynamics-based approach, the thermodynamics associated with the manufacture of automobiles can be examined. Specifically, we can consider the amount of thermodynamic potential consumed in mining and manufacturing from "new" raw materials, the amount consumed in recycling processes, and the minimum requirements for an ideally efficient process. The criterion used is one of "thermodynamic thrift," i.e., the idea that it is desirable to minimize the consumption of thermodynamic potential in achieving any particular goal. There are three policies to consider in this regard: 1) maximizing recycling, 2) extending the useful life of goods, and 3) developing more thermodynamically efficient processes for producing the goods in the first instance.

Each step of the manufacturing process involves the transformation of matter from one state to another, via transformation processes that include mining and smelting, manufacturing, normal use, recycling, junking, and natural degradation. Through numerous, complex calculations, actual figures for loss of thermodynamic potential have been calculated in units of total kilowatt hours (kwh) per automobile. An estimate of 5000-6525 kwh per automobile emerges. The estimate of the *ideal* thermodynamic potential requirement for producing an automobile, on the other hand, is only about 30 kwh.

The enormous magnitude of the gap between actual and ideal thermodynamic potential costs is striking. From this it is evident that our current manufacturing and mining processes "are reflections of the historically developed means of production and transport, rather than of the thermodynamic requirements for creating the ordered structure of an operable machine."(12) The staggering inefficiency manifest in these figures clearly implies the existence of possibilities for vast savings in thermodynamic potential. Even modest improvements in productive processes could generate savings of thousands of kwh per vehicle.

The potential savings from the alternative policy approaches of recycling or extending product life are smaller but significant. Recycling might save between zero and a little over 1000 kwh per vehicle at best. A limitation of these savings from recycling is the need of new car manufacture for some new materials, mostly to maintain the strength of the vehicles, so the savings figures should be halved. Furthermore, even these savings may not be realizable with current recycling technologies. This assessment could change, however, with improved recycling technologies or an increase in the energy costs of mining and smelting.

The savings associated with an extension of the useful life of a product - e.g., through enhanced precision in the manufacturing process itself, or improved maintenance procedures - are somewhat harder to quantify. It is certain, however, that the increased costs of more durable manufacture would be somewhat less than the costs associated with the manufacture of a new product. Doubling or tripling the useful life of an automobile could reduce the overall manufacturing costs by perhaps 1000 kwh, and when the reduced mining and smelting needs are factored in, the net savings increase to 2750-4500 kwh per vehicle.

These figures provide a compelling picture of the differences between these three choices: given current technologies, recycling provides small savings at best when compared to those associated with extending product life, which are in turn small compared with the possible savings from new technologies. However, while it is clear which policy would maximize thermodynamic thrift, the relative ease of adopting one policy over another must also be considered. A policy to encourage maximum recycling would require a relatively small perturbation of existing processes. The extension of useful product life, however, would be more difficult, as it requires a change in both manufacturing techniques and consumer attitudes. The basic technologies to implement the ideal system probably do not yet exist, and the costs of developing and especially of implementing them will be very large indeed. However, the potential savings from their development are so vast that the costs will be insignificant in comparison. For example, it is estimated that saving 1000 kwh per vehicle would equal the output of 8 to 10 large power generation facilities.

It is clear from the example of automobile manufacturing that a policy of thermodynamic thrift ought to be pursued as a national goal. A three stage course seems desirable: to encourage recycling, to develop extended life machines, and to pursue the longer-term goal of developing technologies that would operate with efficiencies closer to the ideal limits. However, the policy implications of this last and most crucial goal are at odds with much current federal policy. We should include in the training of scientists and engineers a specific orientation to conducting this type of research. We should also direct public funds and effort into the development of these technologies since, like military and space technologies, the requisite scale of development is too vast for the private sector.