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Entropy Based Analytic Techniques

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Abstract

The study of energy supply futures is simplified when the end use of this energy is included in the analyses. The various supply and end use opportunities can be evaluated against a standard basis with the analytic techniques discussed here. A simplified theoretical background for these techniques is given and a wide range of energy supply and end use situations to which the techniques apply is presented.

1. INTRODUCTION

There are many difficult issues that arise when the problem of supplying energy for the future is addressed without considering the ultimate use of this energy. These issues were first generally recognized when the 1973-74 oil embargo brought an end to the era of cheap, reliably supplied oil. Its replacement, an era characterized by expensive oil and tentative supplies, has created a period of unprecedented political and economic instability and uncertainty for the United States. These conditions exist because dependence on imported oil has made the United States vulnerable to unpredictable supply interruptions and price increases. Thus, the nation's foreign policy is constrained, war is a continual threat, and the cost of imported oil has caused a drop in national income and high internal inflation.

In the seven years since the embargo, the amount of oil imported by the United States has almost doubled and it now accounts for approximately 50% of the country's oil supply. If the growth of oil imports continues as it has until the mid-1980's, an additional 5 million barrels of oil a day will be imported which will add an additional $38 billion per year cost for imported oil.

On the positive side, the value of known national reserves has increased by $400 billion. The economic issue is further complicated by the fact that there is an existing subsidy of approximately $15 billion a year to oil users in the form of price controls and other policies.

When the magnitude of the economic factors involved with the energy supply problem is brought forth and the political problems of determining how the enormous costs and benefits will be distributed are considered, the virtual paralysis in government energy policy that has existed for the seven years since the embargo is not surprising. These economic and political issues seem to have put the questions concerning replacement energy sources a distant second in terms of actual government priorities.

It is apparently taken as a matter of faith that technology will come to the rescue. Thus such possibilities as a coal based future, the nuclear option, and synthetic fuels are bandied about without a great deal of thought. The immense economic and environmental costs which threaten the very existence of the present culture are only considered superficially. And that these options might not be feasible is unthinkable.

Many of these issues can be ameliorated or eliminated by including the end use of energy supplies in the study of the energy future. The resultant reduction in the scope of the energy supply problem occurs when the end use of the energy is included because a simple analysis shows that energy is used inefficiently in end use applications. By increasing the end use efficiency, the future energy supply requirements can be substantially reduced. This is illustrated by the following data.

Approximately 27 percent of the energy used in the United States goes to residential space conditioning and water heating. This energy is used with an average efficiency of 6 percent when analyzed using an entropy based analytic technique. A similar analysis of the approximately 36 percent on the energy supplied to the industrial sector shows that this energy is used with an average efficiency of 28 percent. Thus approximately 63 percent of the energy supplied in the United States is used with an average efficiency of slightly over 17 percent. This situation provides a wide open, relatively inexpensive opportunity to substantially reduce the energy supply requirements for the future.

It is estimated that approximately 40 percent of the energy used in the United States could be saved with substantially no change in current styles of life. This prediction is supported by the fact that energy conservation efforts have repeatedly demonstrated savings of the predicted level. For instance, savings of 20 percent are routine through the use of simple housekeeping modifications. The achievement of the 40 percent savings requires modest capitol investments. The predicted level of energy savings would eliminate or substantially reduce the level of oil imports for decades to come and the techniques and modifications required are virtually nonpolluting, inexpensive, require little or no development, and are readily available on short notice.

The entropy based analytic technqiues mentioned above and the source of the predictions concerning the opportunities provided by energy conservation are valuable tools for analyzing energy supply and utilization situations at every level. The major significance of these techniques is that they allow the energy requirements for both supply and end use to be made commensurable. That is to say, the quality as well as the quantity requirements at both ends of the energy cycle can be dealt with through the common measure of available work or free energy.

There follows, in turn, a discussion of the second law of thermodynamics and the quality of energy, entropy based analytic techniques, and results of analyses using these techniques.

2. THE SECOND LAW AND THE QUALITY OF ENERGY

The features of the second law of thermodynamics, the entropy law, that are germain to the understanding of entropy based analytic techniques are presented in this section. The second law is often considered obscure or difficult to understand because it can be stated in so many forms. The first statement of the second law was made by Sadi Carnot in about 1820 when he showed that the maximum theoretical efficiency of a steam engine is determined by the temperature of its boiler and the temperature of its condenser. More generally, this says that the theoretical efficiency with which heat energy can be converted to work depends on the temperature at which the heat is transferred.

The generalized modern form of the second law was stated in 1850 by Clausius as follows: The total change in the entropy of a system undergoing a process (a transformation) is always greater than or equal to zero. The "equal to zero" constraint on the second law allows the theoretical upper limit for ideal thermodynamic processes to be determined. This constraint will be used later to demonstrate the concept of the quality of energy.

In order to compactly illustrate the use of the second law and to define the meaning of the change in entropy, the second law will be stated in equation form for the case of constant temperature or infinite capacity reservoirs. A constant temperature reservoir is a body with such a large heat capacity that the addition or subtraction of a small quantity of heat will not change its temperature. For example, the temperature of the Pacific Ocean would not be measurably changed by the addition of 100 gallons of boiling water.

For the case of a constant temperature reservoir, the second law of thermodynamics can be written in equation form as,

$$\Delta S_1 + \Delta S_2 + \ldots + \Delta S_n = 0 \qquad (1)$$

where

ΔS_i is the change in entropy of one step in a process.

The term ΔS_i can be defined as follows:

$$\Delta S_i = \frac{\Delta Q_i}{T_i} \qquad (2)$$

where

ΔQ_i is the amount of heat energy added to the reservoir. Energy added is positive. Energy subtracted is negative, and

T_i is the absolute temperature of the reservoir. Absolute temperature is measured from the point where a body has no more heat available to give up for conversion to work. In general, it is not the case that there is no molecular motion at absolute zero.

As can be seen in Eqs. 1 and 2, the change in entropy depends on the quantity of heat transferred and the temperature at which this transfer takes place. To illustrate the use of the second law of thermodynamics in this form, the maximum amount of work that can theoretically be extracted from heat being transferred from a high temperature to a low temperature reservoir will be determined.

Since a thermodynamic limit is desired, Eq. 1 will be used with the right hand side equated to zero as previously discussed. That is to say, the total change in entropy must be zero. Thus the change in entropy due to the heat transferred from the high temperature reservoir must equal the change in entropy added to the low temperature reservoir. In equation form this can be written as

$$\Delta S_h + \Delta S_\ell = 0 \qquad (3)$$

where

ΔS_h is the change in entropy due to the heat transferred from the high temperature reservoir, and

ΔS_ℓ is the change in entropy due to the heat transferred to the low temperature reservoir.

This equation can be written in terms of Eq. 2 and then rearranged as follows,

$$-\frac{Q_h}{T_h} + \frac{Q_\ell}{T_\ell} = 0$$

or

$$Q_\ell = Q_h \frac{T_\ell}{T_h} \qquad (4)$$

where

Q_h is the quantity of heat transferred from the high temperature reservoir,

Q_ℓ is the quantity of heat transferred to the low temperature reservoir,

T_h is the absolute temperature of the high temperature reservoir, and

T_ℓ is the absolute temperature of the low temperature reservoir.

The meaning of Eq. 4 is quite clear. If the change in entropy is to be zero, the quantity of heat transferred to the low temperature reservoir is smaller than the quantity of heat transferred from the high temperature reservoir. Since the conservation of energy law, the first law of thermodynamics, must hold, the difference between the heat leaving the high temperature reservoir and heat entering the low temperature reservoir must have been converted to mechanical work. This can be written in terms of Eq. 4 as,

$$\begin{aligned} W &= Q_h - Q_\ell \\ &= Q_h \left(1 - \frac{T_\ell}{T_h}\right) \end{aligned}$$

where

W is the theoretical maximum amount of mechanical work that can be extracted from the quantity of heat, Q_h, by a thermodynamically ideal process operating between two reservoirs of different temperature.

There is an important observation that can be made at this point. If the low temperature reservoir is taken as a specific constant temperature, as would be the case if the condenser of a steam engine was cooled by the ambient air. The theoretical maximum amount of work that can be extracted from a given quantity of heat depends only on the temperature of the high temperature reservoir. It can be seen that the higher the temperature, the larger the quantity of work that can be extracted from a quantity of heat. Because, in general, the desired objective is mechanical work, the higher the temperature of the heat, the more valuable it is. That is to say, heat at a high temperature contains more available mechanical work than does heat at a lower temperature. Thus, various states or kinds of energy can be ordered according to the amounts of available work they contain. Mechanical work has the highest value and is the most desirable because it can directly provide shaft works. Electrical energy is almost as valuable as mechanical work because it can provide shaft work with little loss in an efficient electric motor. High temperature heat is more valuable than low temperature heat because more mechanical work can be extracted from a given quantity of high temperature heat. Thus a fuel is as valuable as the amount of electricity or the amount of high temperature heat it can produce.

The major accomplishment of this application of the laws of thermodynamics has been to show that the quality or value of a particular form of energy can be determined in terms of its capacity to do mechanical work. This capacity is commonly referred to as the "availability" (to do mechanical work) of the energy. The availability or available mechanical work in a quantity of energy can be partially or totally consumed when it undergoes a transformation. The value of this measure is illustrated by the following example. Suppose a gallon of oil, which can produce a flame of several hundred degrees, is used to heat a large tank of water to a few degrees above the ambient temperature. Although the quantity of energy added to the water can be nearly equal to the quantity of energy contained in the oil before it was burned, the quality of the energy (the availability to do mechanical work) in the oil has been largely degraded by combustion in heating the water. The quality of energy lost cannot be recovered. It is irreversibly lost. The quantity of energy in the system is not decreased by the combustion of the oil, but the quality of energy is forever reduced. As can be seen, energy in the form of oil is far more valuable than the same quantity of energy in a tank of water heated a few degrees above ambient temperature. That is to say, more mechanical work can be extracted from a gallon of oil than can be extracted from a quantity of water heated a few degrees by this oil.

Thus the energy crisis is connected with the consumption of energy quality, not energy quantity. Since this is the case, the manner in which energy is used must be considered on the same level and in the same thought when considering future sources of energy. The concept of available work or availability provides a measure that aids in this process since various energy sources and energy uses can be directly compared in terms of the amount of available work they consume or supply.

The next section illustrates the use of the availability concept in the development of the entropy based analytic techniques.

3. ENTROPY BASED ANALYSES TECHNIQUES

Although the use of available work for the analyses of supply and end use of energy has only recently come to the attention of a wide and diverse audience, the concept has its origin primarily in the work performed at the end of the last century by J. Willard Gibbs. Development and use of the concept has continued steadily over the years. In recent, years, the Europeans and Russians have done more work on the subject than have the Americans. The Russians have been particularly active in applying the concept to cryogenic problems (1). The recent popularization in the United States of the concept in terms of what is currently called second law efficiency analysis is attributed by many to an article by Charles A. Berg and by a book published in 1975 by the American Physical Society entitled, The Efficient Use of Energy (2,3,4). An extensive history of the availability concept is contained in a letter to the editor of Mechanical Engineer in October, 1977 (5).

The concept of available work supplies the heart of entropy based analytic techniques by providing a yardstick to measure the amount of unrecoverable energy quality consumed by a process. This common measure of performance allows methods unrelated by any other quantity to be compared by their ability to improve a process. For example, the improvement in a process resulting from the installation of a more efficient heat exchanger can be compared to the improvement resulting from more precise control of the process.

It is this feature that gives these methods the versatility to determine the efficiency of processes, provide guidance in determining policy, and to define fertile research areas.

Two widely used entropy based analytic techniques are exergy analyses, which are also known as essergy or availability analyses, and second law of thermodynamics analyses. In the first of these techniques, the available work consumed in each step of an overall process is determined and an attempt is made to improve the efficiency of the process by focusing on the areas consuming large amounts of available work. A recent book entitled, Exergy Analyses and Applications, provides a good overview of the development and application of this method (1). It contains 82 references.

The second technique is similar to the first but for the addition of one step. This step requires the determination of the available work consumed by the ideal thermodynamic process performing the same task. The actual consumption is compared to the theoretical consumption to give what is called the second law efficiency. In equation form the second law of thermodynamic efficiency (Eff_2) can be written as

$$Eff_2 = B_{ideal}/B_{actual}$$

where

B_{ideal} is the minimum thermodynamic ideal amount of available work that is required to perform a task, and

B_{actual} is the amount of available work that is actually consumed in performing a task.

References 2, 3, and 4 contain the required background for the understanding and application of second law efficiency analysis. A slightly different definition of second law efficiency is presented in a recent paper by Rotty and Van Artsdalen (6). This paper redefines second law efficiency in terms of the commonly used definition of efficiency and presents a good argument for replacing the term, second law efficiency, by the term thermodynamic efficiency.

The second law efficiency (Eff_2) is a task oriented concept. It measures how closely the performance of a device accomplishing a specific task compares to the optimal performance permitted by the laws of thermodynamics.

Second law efficiency focuses on the fundamental laws of thermodynamics instead of on the details of a specific device. The information provided by this approach aids scientists and engineers by defining the minimum energy path required to perform a specific task by highlighting areas where excessive amounts of available work are actually consumed. These are areas where positive scientific and technological contributions can be made to improve energy consumption patterns. A list of 73 research opportunities determined by this process is contained in reference 4.

The guidance provided by this type of analyses shows that the negative paths of focusing only on use curtailment and energy supply can be replaced with positive contributions by scientific and technical developments in matching supply and end use requirements. Or as stated in The Efficient Use of Energy (4), p. 8:

> We believe that the use of second law efficiencies and available work, ..., offers new and

> powerful tools for seeking areas where research payoffs can be large. At present our energy resources are being consumed with an overall average second law efficiency of only 10 to 15 percent. It is not only wasteful, but inelegant; there is much room for improvement, for designing our machines to be technically excellent and to reflect the powerful insights of modern science and technology.

Examples of the results of applying entropy based analytic techniques and other areas to which they have been successfully applied are presented in the next section.

4. RESULTS AND AREAS OF APPLICATION

Entropy based analyses techniques have been applied with good results to the study and solution of energy supply and end use patterns and problems at all levels. The results of a wide range of such applications is presented next.

The end use efficiency of the major consumers of energy in the United States have been assessed and the condensed results are as follows (4). Approximately 26.5 percent of the total energy of the nation is used in residential heating and cooling applications. This energy is used with an end use efficiency of approximately 5.3 percent. Approximately 36.0 percent of the energy budget of the country is used in industrial applications with an average end use efficiency of 27.6 percent.

It has been estimated that the technically and economically feasible savings presently available are equal to approximately 40 percent of the total energy usage for the country (7). Savings of this magnitude would greatly reduce if not eliminate the need for imported oil. Methods for accomplishing these goals which were identified using second law efficiency analyses range from the installation of weatherstripping to the use of simultaneous generation of heat and electricity (4,8).

A similar type of study concerning the energy savings possible in small commercial type buildings (offices, apartments, and schools of under 75,000 sq.ft.) through the use of automated energy management systems has been performed (9,10). The purpose of this study was to determine the market potential for a small automated control system for such buildings. The presently available automated control systems are designed for much larger and complex buildings and are therefore too expensive to justify for these small buildings. Single function controls are not adequate for the job. It was found that these types of buildings consume approximately 10.2 percent of the nation's energy. It was estimated that 20 percent of the energy consumed in these buildings could be saved with automated control systems. Thus a good market seems to exist for small automated control systems for these types of buildings. This is a case where existing technology is available for new and retrofit applications.

The actual possibility of reaching these predicted levels of saving has been repeatedly demonstrated. As a consequence of the 1973-74 oil embargo, Los Angeles experienced a cut off of a major proportion of its low sulphur oil supply. Mandatory levels of reduction were set for various energy consuming sectors with penalties for not meeting the goals. A reduction of 18 percent in electrical demand resulted, primarily through better control of lighting and air conditioning (7). A similar savings (19.1 percent) in steam usage has been accomplished at the University of Colorado with virtually no capitol expenditures (11). The savings are primarily due to better maintenance and operating procedures. Many other similar results have been reported.

The example of Dow Chemical Corporation is often cited as a classic example of the success of energy conservation. Through careful energy management, high level management interest and capitol expenditures, this corporation has reduced its energy consumption per pound of product by 40 percent (7,12).

In another application, the end use matching technique was used to determine the possible market for solar energy in industrial process heat applications. Briefly, it was found that presently available solar technology was capable of being applied to 53 percent of the nation's industrial process heat requirements (13). This isn't to say that solar energy can feasibly supply all of this energy, but the replacement of a large fraction of this energy by solar energy is technically possible. It is at this point where the conflicts between the cost of new energy supplies, the cost of subsidized current energy supplies, and the cost of energy conservation techniques arise. Solar energy would be much more competitive against unsubsidized energy, but as is usually the case the cost of conservation is less than any new source of supply. Thus, in a totally free market situation, the reduction of the energy requirements due to conservation would have to be determined in order to estimate the actual solar potential.

Entropy based analyses techniques have been used to analyze many specific technological applications. A few examples follow:

(1) Analysis of solar energy systems (14,15)

(2) Heat exchanger design (16,17,18)

(3) Power consuming and power producing processes (19,20,21,22)

(4) Cogeneration of heat and electricity (4,8,23)

(5) Cryogenics applications (1)

(6) Ocean thermal energy conversion (24)

The analytic techniques based on the concept of available work allow requirements for both supply and end use to be made commensurable. These methods assist at the detailed process level to determine the available work requirements for individual processes, by identifying conservation opportunities, and by defining possible areas of fruitful research. On the policy level, these methods provide assistance by supplying a consistent and unifying overview for energy matters. In addition to assisting in answering policy level questions, these methods assist in determining the proper policy questions to ask.

5. OVERALL PERSPECTIVE AND SUMMARY

The question arises as to why the government which is seemingly in search of a coherent and workable energy policy has not embraced energy conservation wholeheartedly and given it full support. A possible answer is that energy conservation does not lend itself to the typical government support program such as the Apollo project or the development of nuclear power and synthetic fuels. The major characteristic of conservation is its diffuse nature. It is not amenable to the ONE big solution. It will require millions of isolated decisions by millions of different people to accomplish the desired level of savings. A large scale conservation effort will require decisions by the President concerning national policy and decisions by the homeowner concerning whether to invest in window quilts or a heat pump.

In spite of the obstacles, interest in the conservation or energy efficiency option is growing and will continue to grow as the costs, both direct and indirect, of not conserving become more apparent. The major educational effort required to successfully implement a massive conservation program will be assisted by the unification provided by the entropy based analytic techniques with their ability to make supply and end use requirements commensurable through the measure of available work.

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