To What End? A Conceptual Framework for the Analysis of Energy Use

DOUGLAS T. GARDNER and
JOHN B. ROBINSON

A clear conceptual framework in which one can adequately understand the process by which energy is used in the economy is not yet available. Over the past 15 years, energy input-output analysis and the end-use approach to energy modelling have emerged as useful analytic tools. There is, however, a need to integrate these frameworks into a coherent and comprehensive whole. This paper provides an initial formulation of such an integrated framework, defines efficiency measures relating to it, and evaluates the usefulness of this approach for energy-demand modelling and forecasting.

Nous ne disposons pas encore d'un cadre conceptuel clair pour appréhender de manière adéquate le processus par lequel l'énergie est utilisée dans l'économie. Au cours des 15 dernières années, l'analyse input-output et l'approche de l'utilisation ultime qu'on a utilisées pour créer des modèles énergétiques se sont révélées des instruments utiles d'analyse. Il faut cependant intégrer ces cadres conceptuels dans un ensemble cohérent. Cet article offre une première formulation d'un tel cadre conceptuel intégré, définit les mesures d'efficacité qui lui sont relatives et évalue l'utilité de cette approche pour ce qui touche à la création de modèles et aux prévisions concernant la demande d'énergie.

Douglas Gardner is in the Department of Industrial Engineering, University of Toronto. John Robinson is Director of the Sustainable Development Research Institute at the University of British Columbia, Vancouver.

1. Introduction

The late 1970s and early 1980s saw an explosion of interest in energy demand analysis due to energy price hikes and supply disruptions. Interest waned somewhat in the latter half of the 1980s with the collapse in oil prices. More recently, however, growing environmental awareness has brought energy demand analysis once more to the fore. This is due largely to the critical role played by energy in the greenhouse effect. More generally, energy use is an important consideration in policies aimed at sustainable development. A key issue in the current policy debate is both the technical feasibility and the cost of changing present energy use patterns in order to reduce harmful environmental side effects. Such policies could be aimed at either more efficient energy use, fuel substitution, or both. While aggregate energy-economic models have been used to examine some of these issues (Manne and Richels, 1990), such analyses are clearly unable to estimate technical limits nor follow in detail the process by which such changes may be achieved. A more detailed analysis is clearly necessary if policies are to be developed and implemented which bring about the desired changes at minimum cost. Understanding how changes in energy use may be achieved requires both a clear conceptual framework of how energy is used in the economy along with efficiency measures to gauge progress toward the desired goal. Concepts from the fields of end-use modelling, energy input-output analysis and thermodynamics are useful in this respect.

Energy end-use models were developed in the late 1970's in response to both the unreliability of conventional forecasting models and the need for more detailed analysis of the potential for increased energy efficiency (Robinson 1982a, 1982b, 1988). End-use models are based on the observation that the demand for energy is a derived demand. That is, no demand exists for energy itself but only for the end-use services that it helps to provide: space conditioning, lighting, and transportation, etc. Given the demand for these energy services and the efficiency with which they are provided, total energy demand may then be calculated.

A related, but separate, research direction has been the development of energy input-output analysis for determining the total energy requirements needed to produce various goods and services (Bullard and Herendeen, 1975; Casler and Wilbur, 1984). Direct energy is the energy used as an immediate input in the production of a given good or service. Indirect energy use is the total energy required to produce other inputs (e.g., materials, equipment, etc.). Both are significant components of energy demand. The sum of the direct and indirect energy required to produce a product or service is said to be embodied in the product or service. Energy input-output analysis explicitly takes account of all direct and embodied energy flows in the economy and thus takes a broader perspective toward energy use than end-use analysis.

The importance of considering indirect energy consumption in addition to direct energy consumption was underlined by a recent report by the US Congress, Office of Technology Assessment (1990). In an energy input-output analysis of the United States over the 1972-1985 period, it concluded that energy was increasingly being consumed indirectly and that the bulk of this increase was due to the rapid growth in demand for services. It also noted that the energy embodied in imported goods and services was equal to one half of direct US energy imports. Lastly, it observed that one fifth of the reduction in energy use over the 1972-1985 period was due to indirect energy savings as energy-intensive materials were used less. These findings strongly suggest the need to analyze energy use in a broader framework than is commonly done.

In order to evaluate the potential for efficiency improvements, efficiency measures relating to a conceptual framework are also needed. As far as possible, these measures should be based on thermodynamic principles. The relatively recent development of second law analysis and the concept of exergy are useful in this respect.

In this paper, we provide an initial formulation of a coherent and comprehensive energy use framework. The main goal of this framework is to serve as a vehicle for the analysis of both current and future energy use patterns. A second goal is to enrich the commonly held mental model of how energy is used, thus possibly widening the range of future energy use scenarios deemed feasible and perhaps desirable. Efficiency measures relating to this framework are then presented, followed by an evaluation of the usefulness of this approach for energy-demand modelling and forecasting.

2. Conceptualization of Energy Demand

The fundamental purpose of energy use is to help satisfy human needs and desires. Energy may be used either directly for this purpose (e.g., to provide space heating, lighting, cooking and transportation) or indirectly (e.g., to produce goods and services which humans consume) (Ayres and Narkus-Kramer, 1976).[1] In this paper, each of these uses of energy will be treated separately. First, however, a generic description of the energy end-use process, a basic component of both the direct and indirect use of energy, will be presented (Robinson, 1983; Gardner, 1987).

2.1 The End-Use Process

The end-use process, depicted graphically in Fig. 1, begins where traditional descriptions of energy use, which trace the processes lying between primary production and secondary use, leave off.[2] The first link in the end-use process chain involves the procurement of secondary or input energy by the consumer. An end-use technology next transforms the input energy into tertiary or useful energy. For example, a residential furnace (an end-use technology) transforms natural gas or fuel oil (input energy) into heat (useful energy). Useful energy is then used by service technologies to provide energy services such as space conditioning, illumination, and transportation. For example, an automobile requires mechanical energy from the engine to provide transportation services, while a house requires a supply of heat from the furnace in order to remain warm. Energy services represent quantifiable measures of human requirements or needs, for example passenger-kilometers of travel, or kilograms of dried clothes.

The service technology, which uses useful energy as an input in the provision of an energy service, defines the boundary between the system that provides the energy service and the environment. In many cases the service technology is the physical system within which the end-use technology operates. The characteristics of the service technology determine the quantity of useful energy required to provide the energy service. Thus, insulation levels and infiltration rates determine the quantity of heat required to heat a home in a given climate; an automobile's drag coefficient and rolling resistance determine the required mechanical energy to travel a certain distance.

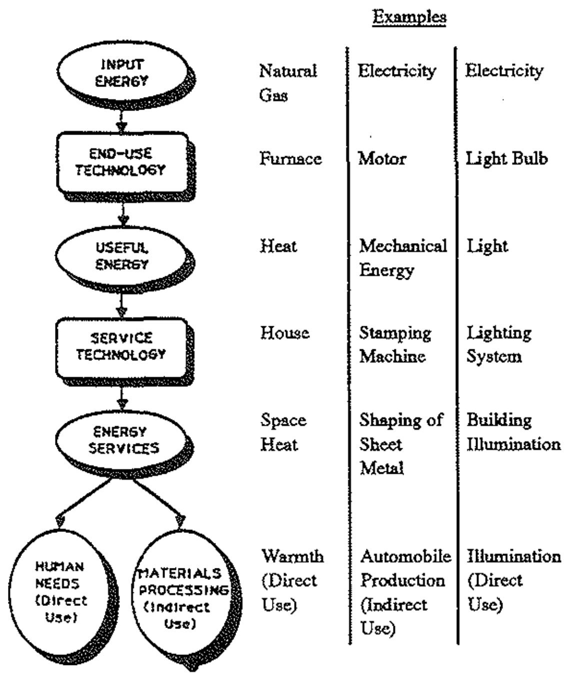

Figure 1: The Energy End-Use Process

2.2 Direct and Indirect Use of Energy

In the direct use of energy, the energy services that are provided are of immediate benefit to humans. Since the goal of the end-use framework is to describe the relationship between energy and human requirements, the end-use process described above is immediately applicable. In the example shown in

1/ Henceforth, "direct use" and "indirect use" of energy will refer to these meanings (i.e., the process of meeting human needs). This terminology is slightly different than that commonly used in energy input-output analysis which applies these terms to any process in which energy is used (e.g., the process of producing a given good or service).

2/ The energy field is bedeviled by complex and sometimes contradictory technical language. In this paper, secondary energy use or input energy is equivalent to what is sometimes called final energy use or even end-use energy: the energy actually purchased by consumers. Tertiary energy use, or output energy, refers to the useful energy output of devices that "utilize" secondary energy, as discussed in more detail in the text.

Fig. 1, space heat (an energy service) meets human requirements for warmth.

Energy that is used indirectly to meet human needs (e.g., for freight transportation, metal refining, fabrication activities), however, is of a fundamentally different nature. It is the goods and services produced by use of this energy that provide energy services directly.

Net energy analysis refers to the estimation of the energy embodied in a given commodity or service (Chapman and Roberts, 1983). For a specific commodity, the gross energy requirement (GER) includes not only the energy used directly in the production process but also the energy used to produce the other inputs to the production process (e.g., materials, buildings, machines, transportation services). Energy input-output analysis has been a major source of the data used in net energy analysis. This methodology uses a modified input-output model to calculate energy intensities for different products which include both direct and indirect energy use. Input-output models are uniquely suited for taking account of the complex network of energy and material flows in the economy.

Figure 2 illustrates a simplified model of material flows and indirect energy use. Primary production describes the processing of raw materials (e.g., iron ore, limestone, wood) into primary materials (e.g., steel, glass, paper, cement). Primary materials are then used in fabrication and assembly processes for the production of material goods. New scrap (i.e., waste material that may be reused), produced in fabrication and assembly processes, is recycled via secondary production. Material goods that are produced then deliver their services over their useful lives. After this period, the materials contained within the goods are either discarded, burned, or salvaged. In the latter case, the materials become old scrap to be reused after secondary production.

Various energy services are required in each of these processing stages. The production of primary materials (steel, glass, cement, etc.) involves the embedding of a substantial portion of the energy used by these industries.[3]

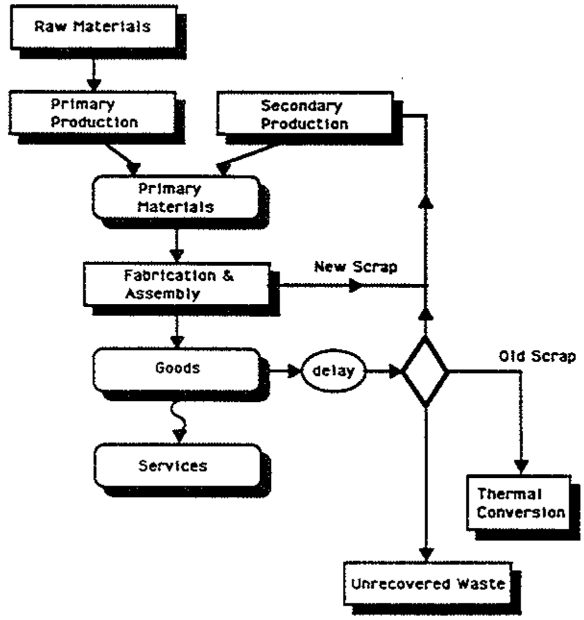

Figure 2: Materials Flows and Indirect Energy Use

The transfer of primary materials or any good containing primary materials thus involves a transfer of energy. Production processes that use recycled materials that contain embedded energy generally require less additional energy than processes that use mainly raw materials (e.g., aluminum). The traditional view of energy demand neglects to take account of these embedded energy flows.

Given this model of indirect energy use, the energy demand process may no longer be seen as a simple flow of energy from producers to consumers. Instead it must be regarded as a complex web of activities involving multiple transformations and transfers of both direct and embedded energy. The term process analysis has been used for the study of such complex material and energy transformation processes (Gault *et al.*, 1985).

3/ Energy which is embedded in a material is not lost to the environment after being used in the production process but is actually contained within the material. The term embodied energy encompasses both embedded energy and energy which is released into the environment after being used.

2.3 The Demand for Energy Services

A focus on the direct and indirect energy flows described above directs attention to the processes and efficiencies by which energy services are provided. However, it takes as given the need for these services or goods. At a more fundamental level, such demands are only a reflection of more basic human needs and desires, ranging from such basic human requirements as food, shelter and warmth to higher needs such as security, communication or self-esteem. Indeed all services, products (which are not desired in themselves but for the services that they provide) and energy demands may be regarded as being derived from human needs and desires. From this perspective, for example, there is no demand for space heat *per se*, but only a need to maintain the physical comfort of the persons in the home.

Such an approach suggests that more efficient ways of meeting these underlying needs may exist or may be envisioned. In principle, it would be desirable to evaluate the efficiency with which energy is used in meeting these more fundamental demands, that is, the relationship between energy services and human needs. In practice, of course, it may be difficult to know exactly what human needs are being satisfied by a specific energy service, let alone how well they are being satisfied.

A second implication is that changes in the composition of these more fundamental demands may affect the demand for various goods and services and thus, by extension, the demand for energy. The terms "structural shift" and "sectoral shift" have been coined to describe this effect. Its influence on energy demand has been documented in a number of recent studies (Huntington, 1989; Marbek, 1989; US Congress, 1990; Howarth *et al.*, 1991; Gardner, 1993). The recent shift away from material-intensive industries is attributed by Williams *et al.* (1987) to be at least partly the result of the growing consumer preference for high value-added, low material-intensive products. Huntington, in a review of a number of studies that have examined this effect, concluded that at least one third of the decline in energy use per unit of output in manufacturing since 1973 may be attributed to this "sectoral shift" (Huntington, 1989). A recent study in Canada concluded that "27% of the total drop in the energy/GDP ratio (from 1972 to 1984) was due to energy efficiency improvements in the business economy and 20% was due to indirect or "structural" change within the business economy" (Marbek 1989, p.A25). It seems clear that a better understanding of the forces driving these changes is necessary. In turn this requires the use of appropriate measures of the efficiency of energy use.

3. Measures of Efficiency

3.1 Thermodynamic Measures of Efficiency

Thermodynamic measures of efficiency may be used whenever energy is converted from one form to another. Thus a thermodynamic measure is called for when measuring the efficiency of a particular end-use technology that converts input energy into useful energy. In addition, a thermodynamic measure is appropriate whenever a process involves a change in chemical or physical state. The production of primary materials from raw materials falls into this category.

When measuring the efficiency of any device that utilizes energy, engineers and other energy analysts have traditionally used the so-called first law efficiency (FLE), defined as the ratio of energy output (in a desirable form) to energy input. This may be written as

$$\eta = \frac{E_2}{E_1},$$

where η is the FLE, E_2 is the energy output (in a desirable form) of the device and E_1 is the actual energy input.[4] In terms of the conceptual

4/ Since for any given end-use technology, the energy output (in a desirable form) is equivalent to the minimum energy requirement, FLE may also be thought of as the ratio of the theoretical minimum energy input of a device to the actual energy input.

framework outlined above, FLE is the efficiency of any end-use technology in converting input energy to useful energy (e.g., the efficiency of a furnace, electric motor, resistance heater, automobile engine, etc.). This is the efficiency measure implicitly assumed in popular discussions of energy efficiency.

The FLE is necessarily device-specific, rather than task-specific. That is, while the FLE of an electric resistance heater tells how efficient a particular heater is, it tells us nothing about the heater's efficiency in the task of using electrical energy to heat a home compared to other means of heating the home.

In order to deal with this problem, there is a need for a method of evaluating energy efficiency independently of the device under question. Energy efficiency must be related to the task being performed. Such an efficiency measure requires the incorporation of the Second Law of thermodynamics, which, unlike the First Law, sets limits on the efficiency of any conversion process or task. The generally accepted definition is a quantity called second law efficiency (SLE) which compares actual performance to optimal performance permitted by both the First and Second Laws. For a single-output device, SLE is the ratio of the "heat or work usefully transferred by a given device" to the "maximum possible heat or work usefully transferable for the same function by any device" (American Institute of Physics, 1975).

For a more complex system, SLE may be defined using the concept of exergy (also known as available work or available energy), defined as the "maximum work that may be provided by a system (or fuel)" (American Institute of Physics, 1975). In any real world process, exergy is consumed, in contrast to energy which is conserved in accordance with the First Law. Thus exergy corresponds to the layman's concept of energy: the "something" which is consumed in any real (i.e., non-ideal) process. While FLE measures the efficiency with which energy is used, SLE measures the efficiency with which exergy is used. It may be defined, in its most general form, as the ratio of the minimum exergy required to perform a task to the actual exergy used. This may be written as

$$\varepsilon = \frac{B_2}{B_1}$$

where ε is the SLE, B_2 is the minimum exergy needed to perform the task and B_1 is the actual exergy used.

The ratio of exergy to energy is known as energy quality, a quantity that may vary between 0 and 1 (Van Gool, 1987). High quality forms of energy include electricity, mechanical energy and chemical energy. The quality of heat energy depends on the ratio of its absolute temperature to that of the general reservoir (e.g., the atmosphere). Using the concept of energy quality, the SLE equation may be rewritten as

$$\varepsilon = \frac{B_2}{B_1} = \frac{C_2 E_2}{C_1 E_1}$$

where C_2 is the minimum required quality of the input energy and C_1 is the actual quality of the input energy (Gyftopoulos and Widmer, 1980). Since E_2/E_1 is simply the FLE, this expression is equivalent to

$$\varepsilon = \frac{C_2}{C_1}\eta$$

This expression is important because it demonstrates that SLE may be interpreted as the product of the FLE and the ratio of the output to input energy qualities. That is, SLE focuses attention not just on the quantity of energy required or produced but also its quality. Improvements in SLE thus depend equally on improvements in FLE and better matching of supplied and required energy qualities.

The difference between FLE and SLE is most pronounced when the task at hand involves heating or cooling. While the FLE of an electric resistance heater used for space heating is 100%, for example, the SLE is only a few percent. The potential for efficiency improvement, rather than being nonexistent as suggested by the FLE, is thus enormous. The mismatching of supplied and required energy qualities (e.g., converting high quality electricity to heat) is a major factor in the low overall efficiency of the economy.

Using the SLE concept, Gyftopoulos and Widmer (1980) have estimated that the overall efficiency of the American economy is very low (8.1%), especially in relation to those sectors where space or process heating comprise major end-uses. Such an analysis, however, still presents an incomplete picture of the theoretical potential for improvement since it considers neither the potential for reducing end-use energy requirements by improving the efficiency of service technologies nor the potential for reducing indirect energy requirements through improved materials practices.[5]

In the industrial sector, for example, the potential savings from increased reuse, recycling, thermal conversion and reduced materials use are not included. A broader and more comprehensive overview of energy use is clearly required incorporating both service technologies and material flows in the economy.

3.2 *Efficiency of the End-Use Process*

As discussed above, the end-use process involves two technologies, each with its own corresponding efficiency. Since end-use and service technologies act in series, the overall efficiency is equal to the product of their respective efficiencies. The efficiency of end-use technologies can be assessed in a straightforward fashion. It consists of the second law efficiency with which those technologies convert input energy into useful energy. However, the situation with regard to service technologies is more complex.

Service technologies are of two types. For certain technologies, a minimum required quantity of useful energy is easily specified given a certain desired level of service. In the case of lighting, for example, a certain minimum amount of light flux (useful energy) must reach the target area in order to provide a given level of illumination. Such services might be referred to as energy-intrinsic services. The efficiency of an energy-intrinsic service technology may be measured using the SLE concept by comparing the minimum exergy required to perform the service to the exergy produced by the end-use technology. Other energy-intrinsic services include cooking, drying and dehumidification.

For certain service technologies, however, it is difficult to specify a minimum theoretical exergy requirement. The amount of heat required to keep a house warm when the external environment is cold, for example, could, in theory, always be reduced by increasing the house's insulation level and air tightness. In the limit, an ideal house would require no internal source of heat. Any real house, when compared to this ideal, would necessarily have an efficiency of zero. Such services might be called energy-extrinsic in the sense that the actual service is not a form of energy. For such services, only a relative measure of efficiency may be used. The Relative Service Efficiency (RSE) of Krause is the ratio of the useful exergy requirements of the state-of-the-art service technology to that of the technology used in providing a given service (Krause, 1981). This measure takes no account of the theoretical potential for improvement in efficiency, but is useful for gauging the practical potential, at least in the near term. Clearly, it is important that a definition of "state-of-the-art" be explicitly specified if the efficiencies obtained are to have meaning. Other energy-extrinsic services include space cooling, refrigeration and transportation (assuming equal initial and final elevations). Table 1 summarizes the end-use process efficiency measures.

3.3 *Direct and Indirect Energy Efficiency*

Since the direct use of energy produces energy services of direct benefit to humans, the end-use process efficiency measures described above may be applied directly. The manner in which energy is used in material processes

5/ This would include, for example, upgrading the insulation level of buildings in order to reduce the quantity of heat (end-use energy) required (see Fig. 1). Using the terminology of the American Institute of Physics, such measures fall under the rubric of "task redefinition," an issue which was explicitly excluded from consideration in this same study.

Table 1: End-use Process Efficiency Measures

	Energy-Intrinsic Services	Energy-Extrinsic Services
End-Use Technology	Second Law Efficiency	Second Law Efficiency
Service Technology	Second Law Efficiency	Relative Service Efficiency

(i.e., indirect energy use), however, is more complex, involving four processes in which energy is either an input or output: primary production, secondary production, fabrication and assembly and scrap processes. Using the framework shown in Fig. 2, methods by which the efficiency of energy used in the production of goods and services may be measured will be presented. As in the analysis of direct energy efficiency, the goal is to enable the assessment of the efficiency with which exergy is used to provide services of benefit to humans.

As an initial step, the energy efficiency of individual operations in materials processes may be evaluated using the end-use process efficiency framework. For example, the efficiency of a metal stamping operation performed by an electrically driven stamping machine may be broken down into the SLE of the electrical motor in converting electricity to mechanical energy and the SLE of the machine in using the mechanical energy to stamp the metal (see Fig. 1). In general, operations with large theoretical minimum exergy requirements are mainly in the primary production stage and involve chemical changes of state. Many operations in fabrication and assembly, secondary production and scrap processing involve only physical rearrangements at the macroscopic level with very small theoretical minimum exergy requirements (Ross, 1985). Large efficiency improvements are thus, in principle, possible.

The fabrication and assembly process also involves engineering technologies that determine the quantities of the various materials in the good being produced and the expected productive lifetime of the good. It seems clear that the potential for improvements in this area is also large. As engineers have learned improved design techniques and gained new knowledge about the nature of materials, the traditional over-designing of all manner of goods has given way to lighter, leaner and less material-intensive designs. This has led to a reduction in the quantity of energy embedded in finished products. Longer-lived products are of obvious benefit, as well, reducing the demand for replacement goods.

Engineering technologies also determine the ease with which scrap materials can be recovered from depleted goods at the end of their useful lives. Exergy embedded in scrap materials may be recovered either through thermal conversion or simply by recycling the material (and its embedded energy) in a new product. Of course, collection, sorting, burning and other ancillary operations associated with scrap processes reduce the net exergy that is recovered. A relative material recovery efficiency may be defined which compares the net exergy actually recovered to that which could be practically recovered with state-of-the-art technology. The preceding efficiency measures or factors are summarized in Table 2.

3.4 Production Efficiency

Developing methods by which the flow and consumption of exergy may be incorporated into an exergy input-output model is beyond the scope of this paper but is an important issue that needs to be addressed in future work. One way in which the efficiency measures described above could be used is to evaluate the overall efficiency of producing a given product. Considering a single good incorporating n primary materials, total indirect exergy expended per unit good (B_{ind}) may be written as

$$B_{ind} = \sum_{i=1}^{n} [q_i(f_i B_{pp*i} + (1-f_i) B_{sp*i})] + B_{fab} - B_{scrap}$$

where q_i is the quantity of material i required per unit good, f_i is the fraction of material i produced in primary production, B_{pp*i} is the exergy required in primary production per

Table 2: Indirect Energy Efficiency Measures

Process	Efficiency Measure or Factor
Primary Production	End-Use Process Measures
Secondary Production	End-Use Process Measures
Fabrication and Assembly • Manufacturing Technology • Engineering Technology	End-Use Process Measures Product Life Material Use Efficiency
Scrap Processing	End-Use Process Measures Material Recovery Efficiency

unit of material i, B_{sp^*i} is the exergy required in secondary production per unit of material i, B_{fab} is the exergy required in fabrication and assembly per unit good and B_{scrap} is the exergy that may be recovered from the depleted good. These terms represent the exergy expended (or gained) per unit good in primary and secondary production, fabrication and assembly and scrap processes, respectively. The exergy expended indirectly per unit of service ($\dot{B}_{ind}$) is

$$\dot{B}_{ind} = \frac{B_{ind}}{L}$$

where L is the expected lifetime in units of service of the good. It is clear from the form of this expression that the expected lifetime of the good is of primary importance. The fraction f of a material produced in primary production as opposed to secondary production can be an important factor if the exergy requirements of secondary production are substantially lower. For goods that contain a large quantity of embedded exergy, the recovery of the scrap materials can also lead to significant savings.

The direct exergy requirement per unit service ($\dot{B}_{dir}$) is simply the direct exergy intensity of a service. For example, an automobile requires a certain number of Joules per kilometre travelled. Adding the direct exergy requirement ($\dot{B}_{dir}$) to the indirect exergy requirement ($\dot{B}_{ind}$) gives the total exergy requirement per unit service ($\dot{B}_{tot}$):

$$\dot{B}_{tot} = \dot{B}_{ind} + \dot{B}_{dir}$$

This expression allows the total system energy required to provide a given energy service or material good to be evaluated. Such an exercise allows the tradeoffs made in any given design to be evaluated, at least within the boundaries previously mentioned.[6] For example, longer-lived automobiles may require heavier parts or more energy-intensive materials; reusable bottles may require more glass than disposables. Similarly, substituting less energy-intensive materials may increase the energy requirements in fabrication and assembly or make the recovery of scrap materials from the depleted good more difficult. For goods that are direct energy users, tradeoffs must also be made between indirect energy use and direct energy use. Substituting aluminum or plastics for steel, for example, may improve the gasoline mileage of automobiles at the expense of increasing their GER as well.

4. Utility of the Conceptual Framework

Despite the developments in end-use modelling methodology, energy input-output analysis and the growing literature on second law efficiency analysis, a common conceptual framework of the end-use process that can be used for modelling and demand analysis is lacking. The need for such a comprehensive framework is particularly apparent in a number of areas of energy policy analysis. The growing complexity of the economy and the rapid growth of the service sector means that the indirect use of energy in the form of vari-

6/ It should be kept in mind that the relationship between human needs and the services provided by energy and material goods has been excluded from this analysis. The analysis of that relationship raises issues that go far beyond questions of physical efficiency.

ous goods and services is increasing relative to the direct use of energy. This trend is likely to accelerate as the economies of both developed and developing nations become more technologically advanced and information-based.

The strength of energy input/output models lies in their ability to systematically measure the total impact on energy use of such changes in demand by linking the inputs and outputs of all sectors of the economy. Their weaknesses lie in the fact that they are based on a static "snapshot" of how energy is used in the economy, one that is typically a number of years out of date. In addition, they are also based on a number of unrealistic assumptions. For example, the demand for different forms of energy (along with all other inputs) is assumed to be strictly proportional to output.[7] Possibilities for fuel substitution, process change or efficiency improvements are excluded. Pinpointing where and how much energy efficiency may be improved is thus difficult.

End-use models, on the other hand, are a technologically based description of how energy is used in the economy. They are thus well suited to the task of exploring the potential for fuel substitution and efficiency improvements through the introduction of new technologies and process changes. Since they are based on a physical description of how energy is used, efficiency measures may be used to evaluate exactly where and how much energy may be saved. In addition, by focusing attention on the link between the tasks which energy performs (e.g., heating) and the services which it helps to provide (e.g., human comfort), end-use models facilitate the process of task redefinition, going beyond strict second law analyses.

They lack, however, the necessary structure to methodically analyze the implications of changing patterns of materials use and demand for goods and services. End-use models (as well as energy input-output models) also neglect, in large part, the exergy embedded in scrap material flows. Thus end-use oriented analyses must be regarded as incomplete measures of the total potential for energy efficiency and substitution, since the potential for many systems savings is ignored. Failure to understand these complex interconnections and the derived nature of energy demand overestimates the present efficiency of energy use, thus necessarily diminishing the range of future scenarios deemed feasible.

Energy input-output models and end-use models thus complement each other in many respects, the weaknesses of one being strengths in the other. Combined with SLE measures and an appreciation of the intimate relationship between energy use and material flows, they could provide a powerful tool for the analysis of both how energy is used and might possibly be used in the future.

A related concern is the problem of energy demand data. A framework for the organization of the available data is needed to facilitate its use in policy design and program evaluation. Moreover, a framework makes clear where new data are needed, allowing priorities for the collection of such data to be set. The need for such a data framework is particularly acute given the paucity and inadequacy of energy end-use data. In the absence of comprehensive end-use data bases, scarce data collection and management resources need to be allocated on the basis of some understanding of which data are likely to be most useful for analysis. In addition, a widely accepted framework would promote the exchange of data among researchers. For example, while it is beyond the scope of this paper to trace the full implications of this framework for data collection efforts, even a cursory overview

---

7/ The method by which the energy required to make different commodities is estimated is also suspect. Many industries produce a number of commodities, some of which are also produced in other industries. The "commodity technology assumption" implies that the energy required to make a given commodity is the same no matter what industry produces it (Casler and Wilbur, 1984). Alternatively, the "industry technology assumption" may be made, implying that the allocation of inputs to the commodities produced by a particular industry should be based on the industry output proportion of each commodity.

suggests the need for data on the age structure and performance characteristics of the energy-using stock, particularly in the industrial sector.

The development of a conceptual framework for energy demand analysis is also bound up with the development of new approaches to energy-demand forecasting. Until the mid-1970s, simple econometric models, trend analysis and expert judgement were virtually the sole sources of analyses of future energy demand. The oil price shocks of the 1970s and the growing concern over environmental problems led to the development of new methodologies in order to illustrate the feasibility of alternative evolution paths of the socioeconomic system. Instead of trying to predict the most likely future, such studies (Solar Energy Research Institute, 1981; Lovins *et al.*, 1982; Brooks *et al.*, 1983; Goldemberg *et al.*, 1988) sought to provide "existence proofs" (Keepin, 1986) of more preferable futures from an economic, social and environmental standpoint.

In order to analyze the potential for improving energy efficiency explicitly, such studies necessarily require an end-use approach, since traditional top-down methodologies are inherently predictive and only implicitly consider the technical processes by which energy is used to provide energy services. However, to date, most analyses of energy efficiency have focused on direct energy use only and on analyzing energy use processes individually and partially, rather than in an integrated and comprehensive fashion. Given the changes in indirect energy use that have occurred in the recent past and the growing complexity of the economy, it seems clear that broader analyses using a comprehensive conceptual framework of energy use are needed if the full potential for change is to be measured.

To date the most extensive application of an end-use approach has occurred in the field of energy demand modelling, especially with regard to electricity modelling and load forecasting. By the mid-1980s, end-use forecasting dominated residential load forecasting in both Canadian and large American utilities, and accounted for one-quarter (US) to one-third (Canada) of commercial sector forecasts, and one-eighth (US) to one-quarter (Canada) of forecasts in the industrial sector (Huss, 1985; Goudie, 1987).

The emergence of end-use modelling and load forecasting is clearly related to changes in the role such forecasts play in utility planning and analysis. The increasing recognition of the possibility of managing electrical demand, rather than simply responding to it, has led to a growing interest in the development of demand-side management (DSM). A key requirement of DSM analysis and planning is the need to understand and model the underlying physical determinants of energy demand. End-use models which in their pure form are simple physical accounting frameworks, devoid of theory or statistically derived behavioural relationships, are ideally suited for the simulation of alternative patterns of electricity use, based for example upon different assumptions about the effects of strategic conservation or strategic load growth programs.

Looking beyond energy modelling *per se*, a focus on both the direct and indirect uses of energy may also be incorporated into the design approach to socioeconomic modelling (Gault *et al.*, 1987). This modelling paradigm, borrowing from control theory, separates the control space, where all information flows occur and control variables are set, from the machine space where all physical flows and transformation processes occur. The design approach emphasizes the use of engineering design information in the description of physical transformation processes, including the requirements for energy and materials. The object of an analysis is not to predict the future, but rather to explore possible alternative scenarios. This goal is facilitated by leaving optimization out of the model and by the accessibility of the control variables to the user.

The design approach to modelling has been implemented in a set of long-term simulation models at Statistics Canada and the University of Waterloo. The Socio-Economic Resource Framework (SERF) consists of a large set of simulation models of the Canadian economy and society (Hoffman and McInnis, 1988). The SERF system incorporates a set of detailed energy end-use models as well as an input-output model. The SERF system is thus well suited for analyses that are concerned with both direct and indirect energy consumption. Recently the SERF system was used to integrate detailed sector-specific analyses of energy efficiency potential into an aggregate "efficiency" scenario of energy use in Canada to the year 2030 (Peat Marwick Stevenson & Kellogg, 1991). While no explicit attempt was made to track indirect and direct energy use, the scenario analysis accounted for the indirect energy used in achieving the energy efficiency potential in each sector.

If the urgent need for better information regarding both the potential and the costs of changing future energy use patterns is to be met, energy models will need to be based upon a consistent and comprehensive representation of the energy use process (Stern, 1984). Only in this way will it be possible to obtain an accurate understanding of the potential for, and implications of, changes in future energy use. There is, of course, a trade-off between increased analytical capability, on the one hand, and the increased cost of gathering energy data and building improved energy use models, on the other (Robinson, 1982a). However, making an informed judgement about that trade-off itself depends on developing a coherent picture of the energy use process that these models and their supporting data are intended to represent. This paper is intended to provide a preliminary outline of one such picture. The next step is to attempt to implement the measures discussed above within an energy modelling framework.

References

American Institute of Physics (1975) *Efficient Use of Energy. Part I - A Physics Perspective*, K.W. Ford, G.I. Rochlin, Marc Ross, R.H. Socolow (eds.) (New York).

Ayres, R.U. and M. Narkus-Kramer (1976) 'An Assessment of Methodologies for Estimating National Energy Efficiency,' American Society of Mechanical Engineers, 76-WA/TS-4.

Braithwait, S. (1987) *End-Use Models: An EPRI Perspective*, paper presented at the Canadian Electrical Association Annual Meeting, Energy Forecasting Section, Calgary, May 6-8.

Brooks, D.B., J.B. Robinson and R.D. Torrie (1983) *2025: Soft Energy Futures for Canada*, Prepared by Friends of the Earth for the Department of Energy, Mines and Resources (Ottawa).

Bullard, C. and R. Herendeen (1975) 'The Energy Costs of Goods and Services,' *Energy Policy* 3.

Casler, S. and S. Wilbur (1984) 'Energy Input-Output Analysis: A Simple Guide,' *Resources and Energy* 6:187-201.

Chapman, P.F. and F. Roberts (1983) *Metal Resources and Energy* (London: Butterworths).

Gardner, D.T. (1987) *Evaluating the Potential for Improved Energy Efficiency with Application to the Socio-Economic Resource Framework (SERF)*, M.A.Sc. dissertation, Department of Systems Design Engineering, University of Waterloo.

—(1993) 'Industrial energy use in Ontario from 1962 to 1984,' *Energy Economics* 15(1):25-32.

Gault, F.D., R.B. Hoffman and B.C. McInnis (1985) 'The Path to Process Data,' *Futures* 17(October): 509-27.

Gault, F.D., K.E. Hamilton, R.B. Hoffman and B.C. McInnis (1987) 'The Design Approach to Socio-Economic Modelling,' *Futures* 19 (February): 3-25.

Goldemberg, J., T.B. Johansson, A.K.N. Reddy and R.H. Williams (1988) *Energy for a Sustainable World* (London: Wiley-Eastern).

Goudie, S.R. (1987) 'How Canadian Electrical Utilities Forecast,' *Proceedings from Canadian Electrical Association Annual Meeting - Energy Forecasting Section*, v.1.

Gyftopoulos, E.P. and T.F. Widmer (1980) 'Benefit-Cost of Energy Conservation,' *Thermodynamics: Second Law Analysis*, R.A.

Gaggioli (ed.) (Washington: American Chemical Society).

Hoffman, R.B. and B.C. McInnis (1988) 'The Evolution of Socio-Economic Modelling in Canada,' *Technological Forecasting and Social Change* 33:311-23.

Howarth, R.B., L. Schipper, P.A. Duerr and S. Strøm (1991) 'Manufacturing Energy Use in Eight OECD Countries,' *Energy Economics* 13(4):135-42.

Huntington, H.G. (1989) 'The Impact of Sectoral Shifts in Industry on U.S. Energy Demands,' *Energy* 14(6):363-72.

Huss, W.R. (1985) 'Can Electric Utilities Improve Their Forecasts?, The Historical Perspective,' *Public Utilities Fortnightly* 116(11):27.

Keepin, B. (1986) 'Review of Global Energy and Carbon Dioxide Projections,' *Annual Review of Energy* 11: 357-82.

Krause, F. (1981) 'The Industrial Economy-An Energy Barrel Without a Bottom?,' *Second International Conference on Soft Energy Paths.* Rome.

Lovins, A.B., L.H. Lovins, F. Krause and W. Bach (1982) *Least-Cost Energy, Solving the CO_2 Problem* (Andover, Massachusetts: Brick House Publishing).

Manne, A.S. and R.G. Richels (1990) 'CO_2 Emission Limits: An Economic Cost Analysis for the U.S.A.,' *The Energy Journal* 11(2):51-74.

Marbek Resource Consultants (1989) *Energy Demand in Canada, 1973-1987 - A Retrospective Analysis, Volume 1: Report*, report prepared for Energy Mines and Resources Canada (Ottawa) revised version, August.

Peat, Marwick, Stevenson and Kellog (1991) *The Economically Attractive Potential for Energy Efficiency Gains in Canada* (Ottawa: Energy, Mines and Resources Canada).

Robinson, J.B. (1982a) 'Bottom-Up Methods and Low-Down Results: Changes in the Estimation of Future Energy Demands,' *Energy* 7(7): 627-35.

—(1982b) 'Energy Backcasting: A proposed method of policy analysis,' *Energy Policy* 10(4): pp. 337-44.

—(1983) *An Energy End-Use Data Framework*, report prepared for Energy Conservation and Oil Substitution Branch, Department of Energy, Mines and Resources, Ottawa.

—(1988) 'Loaded Questions: New Approaches to Utility Load Forecasting,' *Energy Policy* 16(1): 58-68.

Ross, M.H. (1985) Industrial Energy Conservation. *Energy Sources: Conservation and Renewables*, AIP Conference Proceedings No. 135, (New York).

Solar Energy Research Institute (1981) *A New Prosperity - Building a Sustainable Energy Future* (Andover Massachusetts: Brick House Publishing).

Stern, P. (ed.) (1984) *Improving Energy Demand Analysis* (Washington: National Academy Press).

US Congress, Office of Technology Assessment (1990) *Energy Use and the U.S. Economy* (Washington: US Government Printing Office).

Van Gool, W. (1987) 'The Value of Energy Carriers,' *Energy* 12(6):509-18.

Williams, R.H., E.D. Larson and M.H. Ross (1987) 'Materials, Affluence and Industrial Energy Use,' *Annual Review of Energy* 12: 99-144.