CORRELATING THERMODYNAMICS AND ECONOMIC INVESTMENTS TO IMPROVE THE RATIONALE FOR ENERGY RESEARCH

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ABSTRACT

The use of exergy to correlate energy-utilization efficiencies and energy research investments is described. Specifically, energy and exergy losses are compared with to energy research and development spending, demonstrating that the latter correlates with energy losses, even though it would be more sensible to allocate energy research and development funding in line with exergy losses, as they represent the actual deviation of efficiency from the ideal. The methodology is outlined and illustrated with two case studies (the province of Ontario, Canada and the United States). The results are expected to be of use to government and public authorities that administer research and development funding and resources and should help improve the effectiveness of such investments.

INTRODUCTION

The energy utilization of a country or region is conventionally analyzed by examining the flows of energy through various sectors of the economy. But energy analysis can be misleading when used to analyze how effectively energy is utilized, and such analyses sometimes indicate the main inefficiencies to be in the wrong sectors and tend to state a technological efficiency higher than actually exists. Many feel that in order to properly assess how well a country or region utilizes its energy resources, an examination of the flows of exergy, rather than energy, through the sectors is required. The author has used exergy analysis to assess energy utilization in various countries, including Canada, Turkey and Saudi Arabia. Many other investigations have also focused on evaluating the energy utilization efficiency of regions and countries (Ertesvag, 2001; Rosen, 1992, 1993; Reistad, 1975; Ayres et al., 2003; Wall, 1990, 1991; Chen and Qi, 2007; Chen and Chen, 2006; Chen et al., 2006; Hammond and Stapleton, 2001; Gasparatos et al., 2008; Warr et al., 2008; Wall, 1987, 1991; 1997; Ertesvag and Mielnik, 2000; Ertesvag, 2005; Ptasinski et al., 2006; Wall et al., 1994; Stepanov, 1995; Ozdogan and Arikol, 1995; Dincer and Rosen, 2013; Ileri and Gurer, 1998; Dincer and Rosen, 2013; Schaeffer and Wirtshafter, 1992; Nakicenovic et al., 1996; Hermann, 2006).

Given that exergy is often viewed as a measure of value of energy resources, research has been carried out on the relation of exergy to economics and several related tools have been developed. Bryant (2007) and others suggest that the first and second laws of thermodynamics have significant implications for economic theory. Further, many researchers observe that exergy, but not energy, is often a consistent measure of economic value, and that accounting and pricing are better performed when based on exergy rather than energy. Several exergy-based economic-analysis techniques have been developed, usually to help determine appropriate allocations of economic resources for optimal or improved systems and operations, aid design efforts, and enhance economic feasibility and profitability. Exergy-based economic techniques include exergoeconomics, thermoeconomics, exergy-based pricing, EXCEM analysis and analysis based on the ratio of thermodynamic loss to capital cost (Gogus, 2005; Tsatsaronis, 1987; Kotas, 1995; Rosen and Dincer, 2013, Yantovskii, 1994; El-Sayed, 2004; Sciubba, 2005; Valero, 2006; Valero et al., 2006a, 2006b; Lazzaretto and Tsatsaronis, 2006). One outcome of this research is the suggestion that financial investments in energy R&D should be related to or guided by exergy rather than energy measures. This work extends that research.

Several researchers have suggested linkages between energy R&D investments and exergy factors (Dincer and Rosen, 2013). However, little research relating exergy efficiencies or inefficiencies to energy R&D for countries or regions appears to have been undertaken. The principal objective of the work reported here is to analyze the R&D allocations in the energy sectors and compare these allocations to sector energy and exergy losses. This investigation is intended to yield insights on how R&D funding and effort can best be allocated. The research utilizes assessments of energy resource use in countries and regions, aimed at determining the efficiency with which energy resources are utilized and based on energy and exergy analyses. Only two preliminary studies have been reported, to the best of the author's knowledge, from over 20 years ago (Gaggioli, 2005, 2003; Lemieux and Rosen, 1989), and these form the basis of the case studies considered here.

APPROACH AND METHODOLOGY

One recommendation by the author a study of Canadian energy utilization (Rosen, 1992) was to analyze R&D funding in Canada or a subset thereof and to compare it to the corresponding energy and exergy efficiencies. The intention of that recommendation was to determine if R&D funding is being allocated as beneficially as possible, by assessing whether R&D allocations were being made based primarily on an energy analysis of a sector or on the more rational exergy analysis. This idea is reinforced by Gaggioli (1985), who wrote, "exergy methods for analyzing 'energy' systems are the key … for the purposes of decision-making for allocation of resources capital [and] research and development efforts. The exergy methods … are a valuable first step for ascertaining likely prospects (opportunities) for cost effective capital expenditures for 'energy' conservation." Some preliminary research in this area was performed by Gaggioli (1985, 1983).

The methodology used in this investigation to compare R&D spending in a system with the energy and exergy losses of that system is based on that utilized by Gaggioli (1985, 1983). The methodology involves four main steps:

1. The country or region is modeled. One model is shown in Fig. 1, where four main economic sectors are considered: residential-commercial (including institutional), industrial, transportation and utility (electrical and other). In analyzing such a system, the energy and exergy flows through the overall system and its sectors are evaluated, and efficiencies and losses are determined. To model and assess the individual sectors, each is broken down into its main categories and the categories are divided into specific types. For instance, transportation can be broken down into land, air and water categories, and several types of transportation can be considered for each category (e.g., road and rail for land transportation). Energy and exergy efficiencies can be determined for each of the processes occurring in the system, the main ones of which are heating (electric, fossil fuel, other), cooling (electric, thermal, other), work production (electric, fossil-fuel), electricity generation and kinetic energy production. The industrial sector is particularly complex due to the range of processes occurring in it (Brown et al., 1985). A reference environment must be specified to evaluate exergy commodities and, in this analysis, a reference environment which simulates the natural environment is utilized.
2. Energy and exergy efficiencies and inefficiencies are evaluated for a region or country, and for its sectors. For energy or exergy, the inefficiency is the difference between one (or 100% on a percentage basis) and the corresponding efficiency. The fraction of the total energy loss for a sector is considered the *perceived inefficiency*. This quantity is believed by many not to represent a true picture of inefficiency, despite public perception (Gaggioli, 1985, 1983, Dincer and Rosen, 2013). The fraction of total exergy loss (internal destructions plus waste emissions) for a sector is considered the *actual inefficiency* or *real inefficiency*. This label is justified, since the value measures how far the efficiency deviates from the ideal efficiency and is therefore meaningful. The perceived and actual inefficiencies for a sector can be determined. For a sector j, for instance,

   Sector j perceived inefficiency = $1 - \eta_j$ =
   (Sector j energy loss)/(Sector j energy input) (1)

   Sector j actual inefficiencies = $1 - \psi_j$ =
   (Sector j exergy loss)/(Sector j exergy input) (2)

   where η_j denotes the energy efficiency and ψ_j the energy efficiency of sector j. It is sometimes more informative to consider the breakdown of the total inefficiencies by sector. Then, we can write

   Fraction of perceived inefficiency for sector j =
   (Sector j energy loss)/(Total energy loss) (3)

   Fraction of actual inefficiency for sector j =
   (Sector j exergy loss)/(Total exergy loss) (4)

3. Funding allocations by the relevant entities (government, private sector, etc.) to R&D in the sectors are acquired and assessed to ensure they are properly interpreted.
4. The R&D funding allocations to the different sectors are compared with the energy and exergy inefficiencies to help assess how the justified the allocations are and to help recommend future allocations.

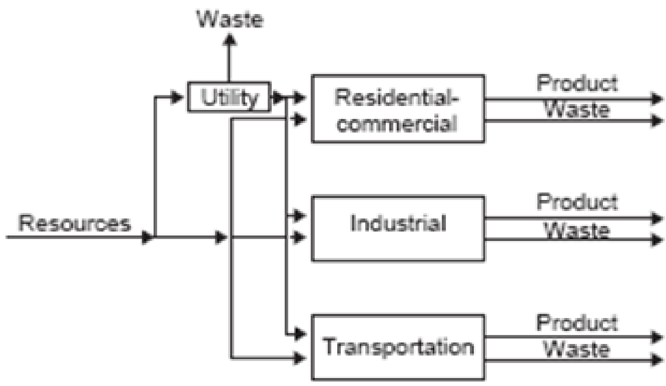

Fig. 1. Model of a region, country or the world, showing flows of resources like energy.

In the next two sections, the author utilizes the methodology described here to compare R&D spending with energy and exergy losses in the United States and in Ontario, Canada. Only two case studies are considered here because only a few analyses like this have been carried out. The case studies are based on previous analyses, and permit the relation between R&D spending and energy and exergy losses in the U.S. and Ontario to be analyzed and contrasted. Although the results presented are based on past data, implications can be inferred from them for the present and future.

CASE STUDY: ONTARIO, CANADA

In this case study, the author uses the methodology described earlier to assess and compare R&D spending with energy and exergy losses, for the province of Ontario, Canada and for its sectors. Ontario is Canada's most populous province and consumes over 30% of all the energy resources used nationally.

Data and analysis

R&D funding data. Energy R&D in Ontario occurs primarily in the private sector and universities. There are three main sources of funding for these projects: the federal and provincial governments and the private sector. A variety of programs within the federal and provincial governments exists from which universities and companies obtain energy research funding, e.g., a major federal funding body is the Natural Sciences and Engineering Research Council (NSERC). Two Ontario funding programs at the time the data for this study were acquired were the University Research Incentive Fund

(URIF) of the Ministry of Colleges and Universities and the Enersearch program of the Ministry of Energy.

Accessing data for all R&D projects in Ontario's energy sector as well as their sources of funding was deemed impractical for the case study due to the variety of R&D sources. For this study, therefore, the authors chose to assess spending only in the Enersearch program. It is expected that research spending trends in this program are somewhat representative of all energy R&D efforts in Ontario, justifying this simplification. This simplification was made for the following reasons (MOE, 1989):

- The requirements for Enersearch funding for a project are broad enough to encompass energy-related projects in all sectors. Enersearch projects are required to address such goals as reducing energy demand through the application of innovative technology to achieve efficient utilization of existing energy sources, developing innovative technology to gain additional supplies from alternative and renewable sources, developing the equipment and capabilities required to utilize these new energy forms, and encouraging replication and use of new energy processes and innovative technologies among potential users.
- The range of activities to which Enersearch applies is broad, and include research and laboratory testing, equipment development and testing, pilot plant equipment, full-scale field trials and technical demonstrations of innovative technologies to determine system performance and economics, initial demonstrations of existing technologies used outside Canada to determine their suitability for application in Ontario, and technology and information transfer of results.
- The program applies to a range of energy technologies, including fuel research and evaluation, transportation, bio-energy conversion, electro-technologies, energy production from waste, residential, industrial and commercial building technologies, energy-efficient industrial processes, heat recovery and recuperation, hydrogen technology, and renewable energy systems.
- A wide variety of organizations can apply for funding under this program, including energy equipment manufacturers and suppliers, industrial and commercial energy users and producer, consulting firms, industrial and research organizations (but excluding electric utilities and publicly funded institutions except when they are in support of private sector proponents).
- Enersearch participated in over sixty projects totalling $27 million between 1986 and 1989, making it the largest government energy R&D program for Ontario.
- The projects undertaken in this program by the participants received an average total government contribution of 33% of their projected eligible net cost. With this substantial yet limited government contribution to the project, the participants incur a large portion of the R&D costs thus projects are typically well planned and thought out. Further, the projects thus directly account for private-sector R&D expenditures as well as those by government.

The funding data were processed to render them suitable for the investigation. In order to analyze the research initiatives under the Enersearch program, a summary of the approved Enersearch projects was obtained (Appendix C of Lemieux and Rosen, 1989; MOE, 1989). These projects are divided into two categories by the Ministry of Energy: projects related to improved energy efficiency and projects related to new energy supply. In order to assess R&D funding for individual sectors, the sector (or sectors) are determined to which each project is most applicable. However, some projects are applicable to more than one sector. Therefore, the sum of the individual sector funding is greater than the actual total funding. The total project cost (Appendix C of Lemieux and Rosen, 1989), which includes both private sector and government funding, is used to determine the total funding for each sector. Sector allocation totals are determined by summing the total project costs of each project in a sector.

Energy and exergy data. Actual inefficiencies and perceived inefficiencies evaluated elsewhere (Section 6.1 of Lemieux and Rosen, 1989, Rosen, 1993) are used. These inefficiencies are determined from the sector and total waste quantities given for Ontario in Fig. 2 for energy and Fig. 3 for exergy. It is observed that 43% of the total energy consumed in Ontario is converted to useful energy. The most efficient sector on an energy basis is the residential sector with an efficiency of 74%, followed closely by the commercial and industrial sectors with efficiencies of 66% and 65% respectively. The least efficient sector on an energy basis is the transportation sector with an efficiency of 18%. The exergy analysis indicates that 24% of Ontario's exergy consumption is converted into useful exergy for end uses. The most efficient sector based on exergy is the industrial sector (45%), followed by the utility sector (39%), the commercial sector (27%), the transportation sector (18%) and finally the residential sector (16%).

The reason for the low exergy efficiencies in the residential and commercial sectors is due to the poor utilization of the quality (or work potential) of the energy entering these sectors. In each of these sectors, the primary use of energy is to produce heat. With the production of heat from a fossil fuel or electrical energy source, there is a loss in the quality of energy that can be reflected only with an exergy analysis. The lower the temperature of the heat produced, the lower is the exergy efficiency. The residential, commercial and industrial sectors exhibit a wide variation between energy and exergy efficiencies. This is attributable to the extent to which heating and cooling processes occur in these sectors.

Results and discussion

Energy R&D budget allocations. The allocations for energy R&D funding in Ontario and each of its five sectors via Enersearch projects for the period May 1986 to April 1989 are listed in Table 3, in absolute terms and as a percentage of the overall budget allocation.

Table 3. R&D Funding Data for All Sectors in Ontario*

Sector	Total project costs ($)	Breakdown of budget allocation (%)
Residential	3,278,524	7
Commercial	1,133,101	2
Industrial	24,793,117	54
Transportation	6,806,834	15
Utility	10,008,471	22
Overall	46,020,047	100

* Data are obtained from MOE (1989).

Based on these data, the sector that receives the most funding is the industrial sector, with approximately 54% of the spending in the Enersearch program. The funding allocations range from 2% ($1,133,101) in the commercial sector to 54%

($24,793,117) in the industrial sector. It is noted that the actual total R&D allocations made through the Enersearch program are approximately $26.8 million and not $46.0 million shown in Table 3. This inflated overall amount is due to the manner in which projects are treated that are applicable to more than one sector, as discussed earlier.

Sector inefficiencies. Inefficiencies for Ontario and each of its sectors are broken down in Table 4, based on data in Figs. 2 and 3.

Table 4. Breakdowns of Sectoral Inefficiencies with Sectoral Energy R&D Budget Allocations for Ontario

Sector	Breakdown of overall inefficiencies		Breakdown of total energy R&D budget allocations (%)
	Portion of perceived inefficiency attributable to sector (%)	Portion of actual inefficiency attributable to sector (%)	
Residential-commercial	12	24	9
Industrial	21	25	54
Transportation	27	20	15
Utility	40	31	22
Overall	100	100	100

A sample calculation for the industrial sector is presented of the breakdown of energy (perceived) and exergy (actual) inefficiencies listed in Table 4. From Fig. 3, it can be seen that the industrial sector contributes 613.5 PJ of waste exergy to the overall waste exergy (2454.3 PJ). Therefore, the actual inefficiency contribution of the industrial sector is as follows:

Industrial sector contribution to overall actual inefficiency
= 613.5/2454.3 = 0.25 (or 25%)

The perceived inefficiency breakdown is calculated similarly but using the waste energy values of Fig. 2, which show that the industrial sector contributes 398.4 PJ of waste energy to the overall waste energy (1875.8 PJ). Therefore,

Industrial sector contrib. to overall perceived inefficiency
= 398.4/1875.8 = 0.21 (or 21%)

Relation between energy sector R&D funding and inefficiencies. The breakdowns of actual and perceived inefficiency values for Ontario and its sectors are compared with the breakdown of values for energy sector R&D funding in Table 4. The breakdown in total energy R&D allocations there is based on data in Table 3. Several trends are evident in Table 4, two of the most prominent of which are as follows:

- Actual inefficiencies exceed perceived inefficiencies in the residential-commercial sector and the industrial sector. For the transportation and utility sectors, the actual inefficiencies are lower than the perceived inefficiencies.
- A relationship is observed between perceived inefficiency and R&D allocations, in that energy R&D budget allocation increases as sector perceived inefficiency increases in Ontario for all sectors (except industrial).

These two trends in the Ontario analysis support the existence of a relationship between R&D allocations and perceived inefficiency levels. It appears that, of all factors affecting energy R&D budget allocations to the sectors, the perceived inefficiency is significant and the actual inefficiency is of less importance or is overlooked. If actual inefficiencies were considered in R&D budget allocations, one would expect to observe more funding for the residential-commercial and utility sectors, because these are the sectors with the largest margins for improvement.

CASE STUDY: UNITED STATES

Data and analysis

Gaggioli applies exergy analysis to the energy utilization in the United States in order to calculate energy sector inefficiencies and then compare them to energy sector R&D funding in the U.S (Gaggioli, 1985, 1983). The main data used in this work are presented in Table 5, which shows the breakdown of actual inefficiencies, as a percentage of total exergy loss in the sector, and the perceived inefficiency, as a percentage of the total energy loss in the sector. These inefficiency breakdowns are calculated using Equations 3 and 4. The budget allocation breakdown in that table lists the amount of funding that was allocated by the United States Department of Energy to sector energy R&D.

Results and discussion

Table 5 shows a clear relationship between the perceived inefficiency and the budget allocations. Although R&D allocations are not based on inefficiency levels alone, the results indicate that budget allocations increase as perceived inefficiencies increase. This leads one to believe that the actual (exergy) inefficiencies are being overlooked when the decision-making for allocating R&D spending is being made.

For example, the two following observations in Table 5 support the statement that R&D funding in the U.S. is based on an energy analysis:

- The utility sector receives the second largest budget allocation of any sector and yet has the least losses on an exergy basis while, on an energy basis, it is second only to the transportation sector as having the most losses.
- The industrial sector which consumes the most energy of any end use sector (Gaggioli, 1985, 1983) and has the most room for improvement on an exergy basis is funded the least mainly because it is perceived as being the most efficient sector on an energy basis.

Table 5. Breakdown of Sectoral Inefficiencies with of Sectoral Energy R&D Budget Allocations for the U.S.*

Sector	Breakdown of overall inefficiencies		Breakdown of total energy R&D budget allocations (%)
	Portion of perceived inefficiency attributable to sector (%)	Portion of actual inefficiency attributable to sector (%)	
Residential-commercial	30	20	20
Industrial	32	15	18
Transportation	24	40	34
Utility	14	25	28
Overall	100	100	100

* Adapted from Gaggioli (1985, 1983).

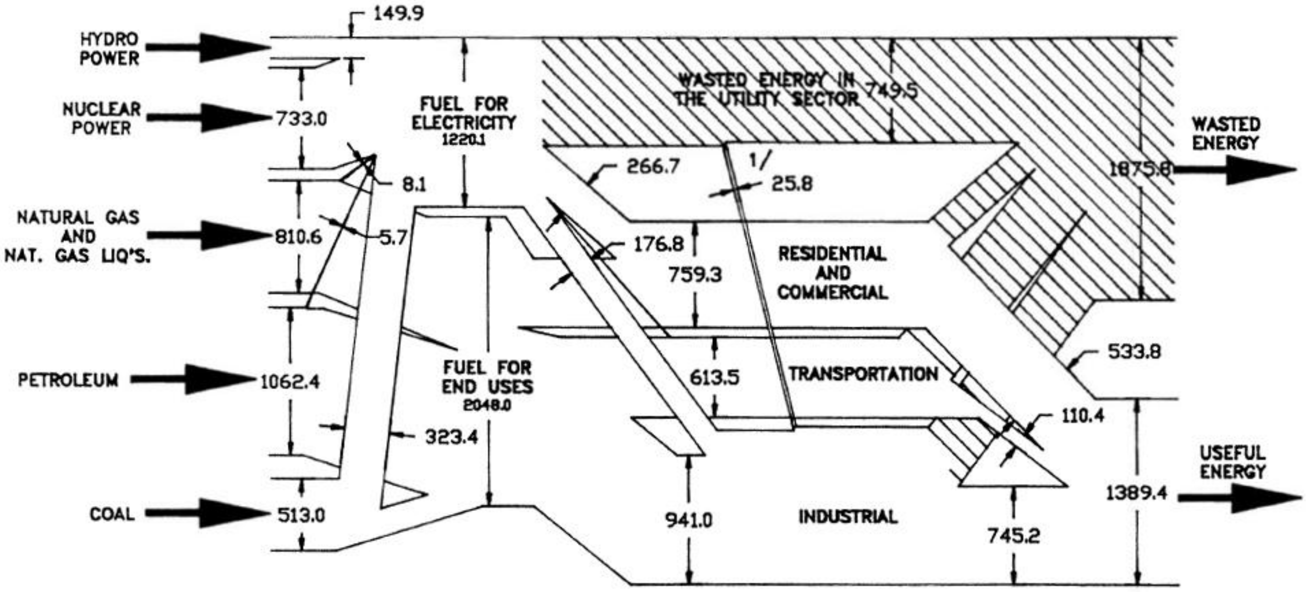

Fig. 2. Energy flow diagram for Ontario (in PJ or 10^{15} J) for 1987. The hatched region denotes losses and the note "1/" indicates steam extracted from the utility sector. Hydraulic energy is shown in kinetic energy equivalent.

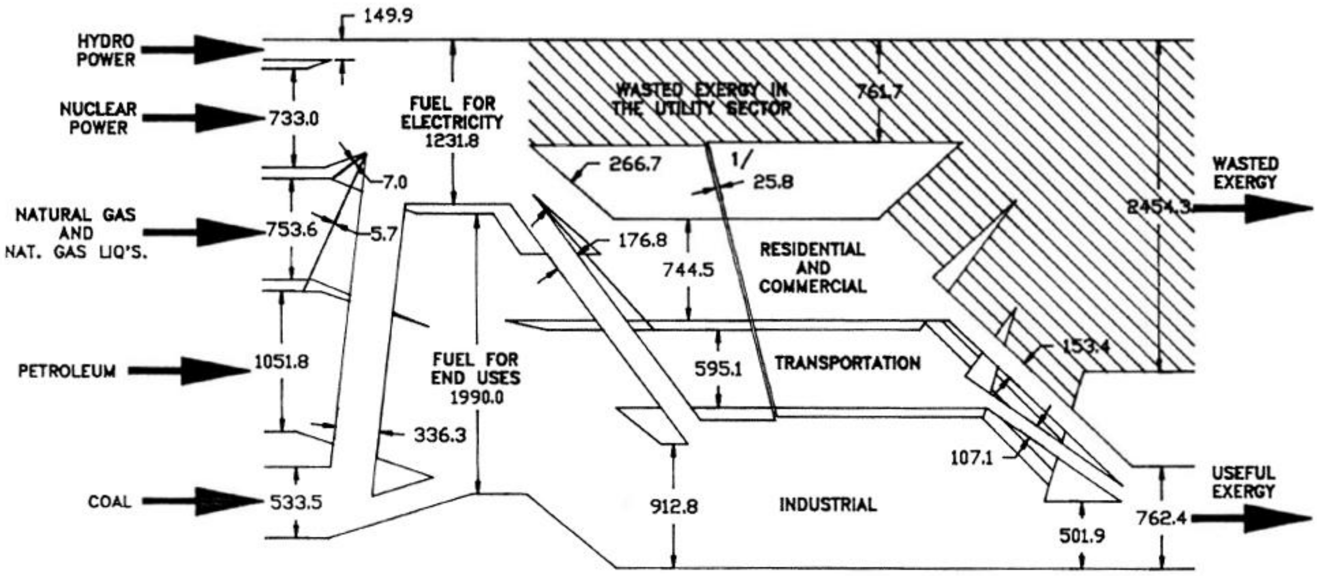

Fig. 3. Exergy flow diagram for Ontario (in PJ or 10^{15} J) for 1987. The hatched region denotes losses (external exergy emissions and internal exergy destructions) and the note "1/" indicates steam extracted from the utility sector. Hydraulic exergy is shown in kinetic exergy equivalent.

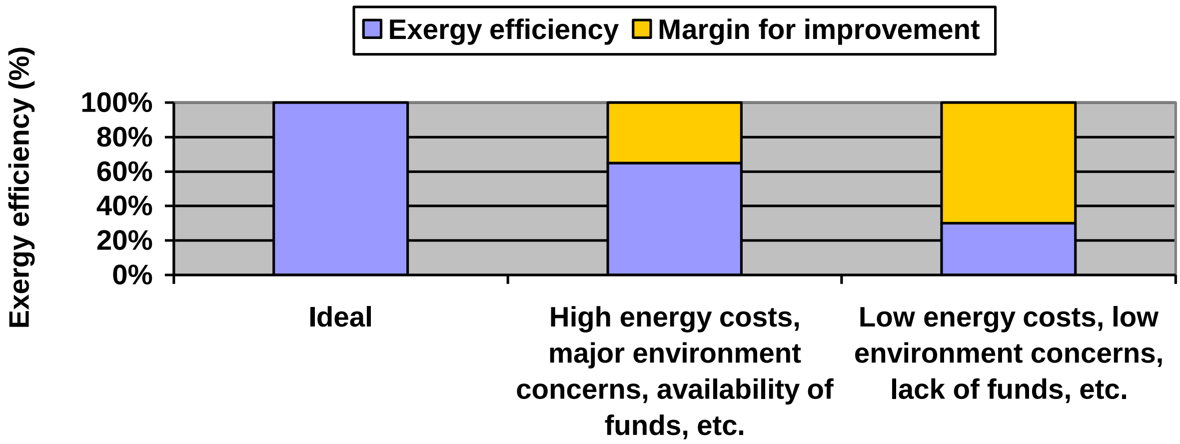

Fig. 4. Comparison of exergy efficiencies and margin for improvement (or actual inefficiency) for regions and countries having various attributes.

DISCUSSION

Comparison of case studies

Several similar trends are exhibited in Table 4 for Ontario and in Table 5 for the U.S. First, in both jurisdictions actual inefficiencies in the residential, commercial and industrial sectors are higher than the perceived inefficiencies, while actual inefficiencies are lower than the perceived inefficiencies for the transportation and utility sectors.

Second, as sector perceived inefficiency increases, energy R&D budget allocation increases in both jurisdictions (except for the Ontario industrial sector). These trends support the general contention that R&D allocations are related to perceived inefficiency levels, while the actual inefficiency is of less importance or neglected. Following actual inefficiencies would direct larger R&D budgets to the residential, commercial and utility sectors to exploit their relatively larger margins for efficiency improvement.

Different behaviour is observed for the industrial sector in Ontario compared to that in the U.S. The industrial sector in Ontario has a perceived inefficiency level of 21% which is higher than anticipated based on perceived efficiencies. The U.S. industrial sector has a perceived inefficiency level of 32% (Table 5) whereas, on the basis of the methodology, one would expect the energy R&D budget allocations for this sector to be between 15% and 9% for Ontario instead of 54% (Table 4). There are several reasons why the industrial sector funding in Ontario is not similar to that for the U.S. Size difference is important, as one jurisdiction is a province with a population exceeding 12 million while the second is a country with a population over 300 million. The U.S. study included all energy R&D funded by the United States Department of Energy which greatly exceeds that of the Enersearch program for Ontario. Not only did the Ontario analysis assess a province instead of a country, it assessed only one of many R&D funding programs in that province. If, for instance, the Ontario report is based R&D budget allocations on all provincial government R&D spending, the trend between perceived inefficiencies and R&D allocations may closer resemble that of the U.S. study. If we go one step further and include all R&D spending allocations in the province by government and private sector sources, the results may be closer still. Some other reasons why the industrial sector funding in Ontario in Table 4 differs from that for the U.S. in Table 5, and is higher than expected, are discussed below:

- The fact that the Enersearch program operates on a two-thirds, one-third funding policy (i.e., 2/3 of the cost of a project is incurred by the participant and 1/3 by the Ministry of Energy) results in participants primarily from industry, and thus may skew energy R&D budget allocations. Approximately 46 of the 55 projects are directly related to specific industrial processes, 19 of which are completely disassociated with any other sector (see Appendix C of Lemieux and Rosen (1989)).
- Electric utilities and publicly funded institutions (e.g., universities, electrical utilities) are not eligible for funding, except in support of private sector proponents. This restriction significantly reduces the number of publicly funded organizations in the program. For instance, only 2 of the 55 projects involve universities. If universities participated more, one would likely see different energy R&D budget allocations to the sectors, and, in particular, less funding to the industrial sector.
- The documentation on the Enersearch program provided by the Ontario Ministry of Energy does not indicate funding amounts on a sector basis. Thus, since the authors had to subjectively estimate the separation of projects into sectors, inaccuracies may have been introduced.
- The large variation in project costs in comparison to the overall budget may also skew the results. For example, it can be seen in Appendix C of Lemieux and Rosen (1989) that the actual total project costs in the Enersearch program for the period considered are $28,678,131 and the individual project costs range from $23,300 to $6,085,100. This large variation in individual project costs in relation to the total budget results in large variations between energy sector funding and may suppress the trend between perceived inefficiencies and R&D budget allocations.
- The fact that other Ontario government ministries also allocate funding to energy R&D for specific sectors (e.g., the Ministry of Transportation likely allocates money for R&D to the transportation sector) may also skew the results. This skewing may be amplified because the Enersearch program may tend not to fund R&D in a sector if a particular ministry is funding it significantly. Therefore, a sector may in reality be receiving considerably more funding than indicated in Table 3.
- The subset or sample group used in this report to assess R&D funding trends is relatively small. To realize more meaningful statistics, it is important to include as many sources of R&D funding as possible when analysing a system. In particular, confidence in the results would increase if a larger sample size were used, preferably by attaining data on the entire R&D spending in the province.

Implications for the present and future

The results of the case studies, although based on past data, have implications for the present and future. The author has begun an investigation of several countries using present and predicted future data and, based on the initial stages of this examination of research funding and energy and exergy efficiencies, many approximate similarities exist between the situation today for many countries and that at the time of the study for Ontario and the U.S., regarding the relation between sectoral energy R&D funding and sectoral inefficiencies. It is thus anticipated that several aspects of the trends indicated by the results of the case studies considered here are likely still valid today. In particular, energy R&D funding appears to be allocated more based on perceived rather than actual efficiencies, thereby potentially missing opportunities for large efficiency gains by focusing on the sectors with the largest margins for efficiency improvement.

It is possible that this trend will continue into the future, unless understanding and appreciation of exergy methods increases and reaches the levels of policy makers and industry leaders. Thus, the need to improve knowledge of exergy in society appears to be of great importance, so that strategic steps can be taken to allocate energy R&D funding where it can be most beneficially utilized.

This discussion can be extended so as to illustrate the variations of exergy efficiencies for regions and countries, characterized by their circumstances and settings, with margin for efficiency improvement, i.e., actual inefficiency. Factors and attributes that characterize the region for purposes of this discussion include energy resource availability and costs, environmental constraints, and availability of funds. Other related factors are also considered implicitly.

Exergy efficiencies and the corresponding margin for efficiency improvement for regions and countries with two sets of realistic characteristics are presented in Fig. 4. Countries and regions with high energy costs and major environment concerns and availability of funds are likely represented by the second bar, while those with low energy costs, low environment concerns and lack of funds are likely represented by the rightmost. These cases likely bracket other regions and countries, i.e., those having some but not all of high energy costs, major environment concerns, availability of funds, etc. The hypothetical case of ideal efficiency is also shown in the figure, both for comparison and because an exergy efficiency of 100% always specifies ideal but unattainable thermodynamic behaviour. Several other important points can be observed in Fig. 4:

- Countries and regions with lower rather than higher exergy efficiencies have greater margins for efficiency improvement, as characterized by actual inefficiencies.
- Low exergy efficiencies often are observed in countries and regions with low energy costs, lax environmental constraints and a lack of funding for efficient technologies, awareness of efficient technologies and processes, and a sufficiently educated and skilled workforce. High exergy efficiencies are usually observed in countries/regions where circumstances foster high efficiency, e.g., high energy costs, funding availability for efficient technologies, available energy export markets, strict environmental constraints or emissions limitations, etc.
- The ultimate margin for efficiency improvement is seen to be the difference between the ideal exergy efficiency of 100%, which applies to ideal processes or devices, and the actual exergy efficiency. An awareness of this limit helps in establishing realistic targets for efficiency improvement.
- When energy-related factors change, countries and regions tend to respond (or should respond as it is usually in their best interests to do so). For instance, countries and regions tend to introduce measures that lead to increased exergy efficiency when energy costs increase or environmental regulations become stricter.
- An important observation for any region or country related to the above point is that exergy efficiency increases when circumstances warrant improved efficiency, but energy efficiencies do not necessarily increase. Appropriate efficiency targets and energy research efforts and support should be established based on exergy, as confusion and waste can result if efforts to determine appropriate efficiency research and targets are based on energy.

Specific regions or countries are not easily identified in Fig. 4 because their characteristics are usually much more complicated than the two simple cases shown. Nonetheless some generalities and trends, which likely apply in some cases, can be pointed out:

- Although the characteristics of countries with developing economies vary greatly, many less developed countries fall into rightmost category in Fig. 4 because for them energy resources are often less affordable (i.e., energy costs are high as a proportion of gross domestic product or average income per capita), obtaining funding for efficient technologies is difficult, and environmental laws are less strict. This behaviour is partly related to the focus of such countries on developing economically and in other ways and/or meeting basic needs.
- Developed or industrialized countries tend to fall into the middle category in Fig. 4, since they usually have high energy costs and readily available mechanisms for exporting energy resources, strict environmental restrictions and laws, and funding for efficient energy conversion and utilization technologies. The wealth of such countries often makes them require or expect energy resources to be used efficiently and cleanly.
- In our globalized economy, it is unlikely that a country would have an extremely low exergy efficiency based on market forces, which exist in a similar form for developed or developing regions, because globalization makes it relatively easy to buy and sell energy commodities.

The ideas discussed here are somewhat confirmed in many countries and regions, where significant disparities exists in factors like energy costs and environmental regulations. In much of Europe and Asia, for example, energy prices are roughly double those in North America, and higher exergy efficiencies are observed. In the future, the ideas discussed in this section suggest that countries and regions are generally likely to move towards higher exergy efficiencies due to factors like energy price increases (long-term), resource scarcities, environmental limitations, and growth in developing economies (which can have very significant impacts for large countries like China and India). An important strategy would be to make investments in energy R&D guided in part by actual rather than perceived inefficiencies, i.e., by exergy factors.

CONCLUSIONS

In comparing energy R&D budget allocations with energy and exergy losses, it appears that of all factors affecting energy R&D budget allocations to the sectors, the perceived inefficiency is significant and the actual inefficiency is of less importance or is overlooked completely. If actual inefficiencies are considered in energy R&D budget allocations, one would probably see more funding for the residential, commercial, and utility sectors, because these are the sectors with a large room for improvement. The results are expected to assist government and public authorities that deal with research and development funding and should help improve the effectiveness of such investments of funds and resources. The comparison made in the case studies between energy R&D spending for the sectors of a region (Ontario) and a country (United States) with energy and exergy inefficiencies in those sectors reinforces these conclusions.

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NOMENCLATURE

Symbol	Quantity	SI Unit
η	energy efficiency	
ψ	exergy efficiency	

Subscripts

j sector j

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