Energy and materials conservation: applying pioneering research and techniques to current non-energy materials conservation issues

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The research of the Energy Research Group (ERG) at the University of Illinois at Urbana-Champaign through the 1970s and early 1980s has recurring bouts of popularity. That research traced the flow of various energy types from nature to the final product or service, using modified economic input–output analysis. That information allowed for a comparison of alternative uses of products and services that delivered the same demand. The goal of the study was to identify the energy-conserving potential of the alternatives. Interest in that research has risen and fallen with the price of energy through three cycles now, with the current interest also encompassing materials conservation. Although the specific numerical results of this work are dated, the process by which the analysis was conducted creates, at least, a suggestion for future analysis in the arena of materials research. A review of the ERG history, including techniques pioneered for investigating the potential for energy conservation and some of the ancillary lessons learned along the way, may be of some use to those working on issues of materials conservation today. In the coming years, the most relevant research will include assessment of the socio-economic–ecological impact of technological materials conservation policies.

1. Introduction

Stored energy forms in nature are materials, as are the ores of iron and aluminium and the trees of our forests.
Historically, we have placed these materials in various categories of concern. Leaders of national policy first worried about running out of energy, but soon realized that copper was also showing signs of scarcity. Long ago, we thought of steel as a material only for making bridges and machines and reinforcing concrete structures. However, throwaway food and drink packaging increased the demand for steel. More recently, we thought of wood primarily as the material for homes, furniture and books until the advent of biomass fuels. When our aim is to conserve energy and materials, how might we usefully distinguish between these resources at their points of origin in nature?

Perhaps the most rewarding way to categorize resources is by their system time constant, or their residence time in the economic system. If a material is destined to have a long residence time (such as a part of a machine or a section of a building), then the conservation policy for that material might differ from the conservation policy for a short-lived material (such as a beer can or a newspaper).

How does this work? Today, aluminium is the dominant material for an aeroplane, and plastic is the dominant material for a soft drink container. Natural gas can be burned to generate steam in an electrical power plant or be converted into plastic parts for computers. In economic terms, this division is between stocks and flows, between capital goods and perishables. Economists somewhat arbitrarily class cars as part of the short-lived flow and houses as long-lived capital stocks.

Most of the energy materials, including coal, refined petroleum, natural gas, uranium, stored reservoir waters and biomass, are destined for short residence times in the economy. They are to become flows in the economic system. Although some fossil energy is used as lubricants or converted to plastic, our main interest is in their low entropy content, the readily available energy in these materials. Clearly, not every pound of these materials is consumed in energy production, but most is, and the policy of conservation of their main use was the focus of the Energy Research Group (ERG) at the University of Illinois at Urbana-Champaign through the 1970s and early 1980s.

The story for the rest of the resource materials, the subject of this paper, is somewhat the reverse. In modern US society, for example, some metals are used for convenience and their time constant is small. Most metals, however, go into such capital goods as buildings and machines, and they reside in the system for a relatively long time with high spatial density. That time is determined by how well the capital is maintained and by changes in technology that may reveal them obsolete as opposed to being beyond maintenance.

The conservation policies depend on the time constant of the materials. Short-time-constant scarce materials are thought of as flows, and these flows would be reduced by conservation policies that focus on substitution, reuse, recycling or changes in consumer demand.

Long-time-constant materials in the form of capital goods would be conserved in the system as long as practicable by a different set of conservation policies. These materials are the ones to be eventually re-used at other points in the economy and ultimately broken down and recycled. Appropriate design strategies can reduce the environmental impacts of producing these materials [1]. The high spatial density of these durable material forms facilitates their maintenance in the system and their eventual recycling.

Of the great array of materials, the first materials to focus on are those deemed scarce and those with high embodied energy. A great deal of information on the complex issue of appropriate resource scarcity measures is available. Is the best measure of a resource unit its cost, or its marginal cost, or its price (marginal cost plus scarcity rent)? This is discussed more fully in a later section.

2. Historic research on energy conservation by the Energy Research Group

Some elements of the decade and a half of work conducted by the ERG could help to inform research policy on scarce materials or on those materials with accompanying large environmental impact. Energy itself is, of course, not recyclable although it can be conserved by material reuse
and recycling. One may find the dilemma of needing to use more of a scarce material in order to conserve energy, or vice versa. Therefore, a thorough knowledge of the energy use implications of materials conservation is imperative. As well, the general strategy of the ERG research on energy use should be useful in establishing a large-scale materials conservation research programme.

Generally, our focus on the total (direct and indirect) energy needed to supply a unit of good or a service should provide a useful technique in filtering out of the economy the hierarchy of demand for specific materials. This information enabled ERG to compare the total energy costs of alternative means for meeting specific demands of consumers, government and the private sector. These results pointed the way towards greater energy conservation.

The ERG used a combined energy-dollar flow input–output (I-O) theory to more accurately track the total (direct and indirect) energy flow from the ground to produce each item of final consumption. This allowed us to assign all the energy consumed in a given year to all of the items of final consumption for that, without multiple counting. With this information, ERG evaluated hundreds of consumption alternative items and processes for their energy-conserving potential. The ERG team developed the energy I-O matrix for 4 years (1963, 1967, 1972 and 1977), as these were the only databases created by the US Census Bureau at the time. This same theory and the data on employment also enabled ERG to calculate the direct and indirect labour costs of each unit of final consumption. This provided a way to address the energy–labour substitutions that were happening in the economy and to estimate the increase in labour demand as energy became increasingly expensive. The same kind of research programme, beginning with I-O analysis, is recommended for materials conservation.

3. History of the energy input–output theory

In the 1930s, Wassily Leontief [2] was putting the finishing touches to his development of economic I-O analysis of the US economy, just in time for its strategic use in converting US industry to a war footing. His process allowed the direct and indirect demands of industry to be estimated for a given gross national product (GNP). The government stated its GNP estimates for the items of war in terms of the numbers of aeroplanes, tanks, guns, explosives and so forth for each of the 4 or 5 years they expected the war to last. Leontief was able to determine, for this final bill of goods, the flows of steel, aluminium, energy and such needed from each industry, directly and indirectly. Capturing the myriad of these indirect inputs for the production of a given product or service is the key contribution of I-O analysis. These flows were compared with the capital stocks needed in these industries to meet the wartime demands. They found that the output of war material and energy plus those of personal consumption was impossible given then-current production capacities in any of the major sectors. Two major endeavours were soon undertaken. First, massive new construction programmes were started in steel production and shipbuilding, including conversion of many industries to the production of military items. For example, the automobile companies converted to the production of military vehicles. Second, citizens were called upon to substantially reduce their personal consumption of cars, gasoline, tyres and certain kinds of food. How did they do it?

Imagine a matrix of exchanges between each entity involved in the production economy. The industries may be very materials-oriented, such as the steel or the automotive industries, or they may be service-oriented, such as the finance or transportation industries. The industries are listed down the rows of the matrix and in the same order across the columns of the matrix. At each intersection in the matrix, the annual exchange between the row industry and the column industry was found from industry records and posted in dollars. The net outputs of each of these industries, their contribution to final demand, were also estimated for the year. The total of all of these net outputs is now known as the gross domestic product (GDP) [3]. Simon Kuznets, who designed the GDP definitions, and Leontief would later get Nobel prizes in economics for their work.

1Final demand is the net output of the economy. It is the sum of personal consumption, government spending, new capital formation, net exports and inventory changes.
The list or vector of net inputs to the economy was also estimated and arranged across the bottom of the exchange matrix. The net inputs were composed of separate vectors of the labour inputs to each industry, their profits, depreciation and taxes paid. The dollar value of the total input of each industry (the column sum) was equal to the total output of each industry (the row sum). With this special set of data, Leontief showed how a total requirements matrix could be calculated. Each element in this derived matrix represented the total direct and indirect requirements from the row industry by the column industry per dollar of that industry’s total output. The total required output of each of the industries was the product of a special form of the inverted exchange matrix times the GDP. By comparing these total outputs with the expanding demands (scenario versions of the GDP), a feasible transition to a wartime economy could be estimated. Private entrepreneurs, such as Henry J. Kaiser, were essentially given blank cheques to build steel and ship construction enterprises at the estimated rates. At the same time, rationing of consumer goods and price controls were put into place. The overall success of this effort is legendary.

After the war, these capacities for production remained, driving the ensuing economy in a variety of new and unique ways. No formal transition plan of reduction was forthcoming, even though the policy-generating process to quickly return to a peacetime economy was at hand. For example, the production of explosives required the production of nitrogen. After the war, these munitions companies desperately sought new uses for their nitrogen. One was found: the production of ammonia as a fertilizer of annual crops, particularly corn. This flood of cheap ammonia contributed to a glut in corn production leading to the current billions in federal revenues spent annually on price-support programmes.

4. The classic input–output theory

The mathematics behind the Leontief idea is rather simple. It is really just an elegant simultaneous solution to a series of linear equations. The idea is to assign all of the economic exchanges uniquely to the products and services produced in the economy in a given year. It captures, for example, the coal needed to make steel—not only that coal used in the steel industry but also the coal, for example, used in the power plants that made the electricity that was used in making steel. The process also captures all of the steel that was used in the economy needed to produce the measured output of steel. The ultimate use of such assignments is to estimate the changes in each of the industrial and commercial outputs needed for one more unit production of any specified product or service.

Let the exchange matrix be \( x \) and the total output of each industry be vector \( X \). Divide the columns in matrix \( x \) by their respective total outputs to form matrix \( A \), the (normalized) direct requirements matrix, whose elements are assumed to be constant for small changes in \( X \), so

\[
x \ast \hat{X}^{-1} = A, \tag{4.1}
\]

a matrix of assumed constants, where \( \hat{X}^{-1} \) is the diagonalized matrix of the inverted elements of vector \( X \).

Then,

\[
A \ast X + Y = X, \tag{4.2}
\]

where vector \( Y \) is the vector of net outputs. (Its sum is the GDP.)

Then,

\[
Y = [I - A] \ast X, \tag{4.3}
\]

where \( I \) is the unity matrix.

Alternatively, to find the vector of required industry outputs for a desired net output \( Y \),

\[
X = [I - A]^{-1} \ast Y, \tag{4.4}
\]

requiring the inversion of matrix \([I - A]\), forming the total requirements matrix.
Equation (4.4) was the basis for the transformation of the US peacetime economy to a war footing in the late 1930s. Thus, for a change in $Y$ (GDP), the corresponding changes in all of the industrial and commercial outputs can be determined.

The $x$ matrix and $Y$ vector are routinely assembled by the Bureau of Economic Analysis in the US Department of Commerce and published about every 5 years.

5. Input–output energy analysis

A simple example will illustrate the inherent complexity of the material–energy problem, which ERG used—several years later—to recast the I-O formalism as a general tool for the analysis of real and embodied quantities in the industrial system.

In 1969, a group of my students analysed the direct and indirect energy use in making and delivering soft drinks and beer in refillable and throwaway containers. The goal was to find out whether the system of refillable containers was more or less energy-intensive than the system of throwaway containers. By that time, glass refillable containers were being rapidly displaced from the market by glass and aluminium throwaway containers. To find as many inputs to this process chain as possible, the research team meticulously traced production of the glass container all the way back to the sand from which it was made. Even the chain of processing of the major inputs to the bottle-making chain, such as the plastic and paper packaging, was involved in the final calculation. It was tedious and time-consuming to find as many inputs to the process chain as possible. Along the way, the enormous difficulty of the infinite regress involved was realized. Several basic forms of energy were identified, and the process was tracked for each of them. The results of this work became extremely popular and were used as the basis for many state legislative attempts to ban or tax these containers as well as many court challenges to the idea of requiring monetary deposits on them. The total throwaway energy cost was determined to be about four times that of the 18-trip (typical) refillable container per unit of beverage. During the same time, Hugh Folk, an economics professor at the University of Illinois at Urbana-Champaign, calculated the direct and indirect labour cost of throwaways and refillables. His team found that the provisioning of refillable containers required more and different jobs than those required for throwaways. The refillable–throwaway container issue is a perfect example of the substitution of a comparatively small material (glass) use by much greater use of a more costly one (aluminium, plastic), more costly in terms of dollars and energy. The results were eventually published formally [4,5].

Several very interesting new issues arose. First was the idea that energy conservation could be achieved by changing one’s product choices—the idea of embodied energy in consumer products—in addition to the reduction in use of heating fuels and gasoline. Although the ERG members were only observers of the complex political process that the study had started, they noted the extreme reactions to the idea of a return to refillables from the industries that made the disposable containers, those that made the material for these containers, those that made paper and plastic packaging for the containers, and the coalition of labour unions. Each group pushed for the throwaway containers. The labour union coalition reaction was especially interesting. (There was then even a refillable bottle washers’ union in the coalition.)

Folk [6] had found that, because the total payments to labour under either system, whether refillable or throwaway, were roughly the same, the average wage within these systems would decline with a return to a more labour-intensive refillable system. This was due to the increase in relatively low-waged jobs at the retail and wholesale levels as well as a decline in the relatively high-waged jobs in the glass, aluminium and container industries. Thus, while the overall labour coalition effect would be an overall increase in jobs, the high union fees paid by the high-waged job holders caused the coalition to lobby for throwaways.

Note that the can of throwaway aluminium was not only a substitute material but also a substitute container.
Research revealed that, while the beer industry had introduced throwaway containers in the 1930s, particularly for the outdoorsman, the major thrust came during the war when beer was shipped to troops at the front. Owing to the scarce shipping capacity, return of the refillables was not appropriate. To continue the movement towards throwaways after the war, the container makers and the metals industries, primarily Reynolds, Alcoa and Inland Steel, would sign special contracts with bottlers such as Coke and Busch. The 5 year contracts yielded free throwaway containers in the first year, with increasingly small discounts as the years progressed. This incentive allowed the bottlers enough savings to convert their bottling lines to throwaways and use one-way delivery trucks to wholesalers and retailers. The advent of the interstate highway system allowed overnight trucking from the new bottling plants, minimizing bottler inventory costs. Big bottlers were then able to successfully invade the territories of smaller bottlers, who used refillable containers exclusively. The big bottlers’ throwaways were of no use to the local bottlers, who soon went out of business. The prodigious use of the throwaway led to significant waste and littering issues. A strong public reaction to this waste was countered by an advertising campaign that spoke of the ecology of the recycled aluminium container and also of wasteful consumer littering, thus turning the issue on its head. The last holdout was the individual grocery shopper buying soft drinks in refillable bottles. Eventually, even that consumer began to use throwaway containers wherever industry-induced local aluminium recycling was instituted. Here is a clear case where recycling programmes increased overall material (aluminium and, later, plastic) use.

A final effort in this area showed that the modern recycled aluminium soft drink or beer container required about twice the total direct and indirect (embodied) system energy as its comparable refillable glass container. Yet in the USA today, the refillable container is a museum item. The rich experience with the energy cost of containers made me realize that this same story could be told for every good or service produced in the economy. By that time, I was recently graduated, had joined the Center for Advanced Computation (CAC), and formed the ERG. The interdisciplinary nature of the CAC allowed for a broad focus, including economics, and that led the way to the I-O theory of Leontief [2].

The study of the container industry showed that energy use and labour are substitutes when the system is viewed overall. And energy and materials use are complements. These observations were later found to be generally true throughout the US economy.

In 1970, I attracted two other newly minted PhDs, Clark Bullard (engineering) and Robert Herendeen (physics) to the study of embodied energy. They each had concerns over the growing dependence of the economy on finite energy resources. The ERG wanted to see whether knowledge of the energy embodied in various products and services would change purchasing decisions towards energy conservation. A goal was to find a way to uniquely assign all of the energy of the various forms that moved from the finite resource base to all of the consumer products and services. The I-O process seemed to hold promise, and with the help of a significant National Science Foundation grant, the research team was on solid footing in 1971, serendipitously just in time for the 1973–1974 oil embargo and price jump.

Examination of the 1963 US Bureau of Economic Analysis (US Department of Commerce) data revealed a particularly extreme variation in the apparent prices paid for energy across the economic sectors. It was abundantly clear that ERG would have to use physical units in the transactions matrix ($A$) rather than the given dollar values of the exchanges. This proved to be an enormous task, but well worth it in the end.

The current process by Carnegie-Mellon University to produce up-to-date energy intensities is significantly flawed because of the physical energy units in the transactions matrix. Instead, they use the given dollar values of energy (ERG found that the price paid for energy varied by a factor of 10 over the full range of commerce and industry).

The ERG published the details of how these calculations were made [7]. (This work was based on the theory in the appendix. An earlier version was based on the $A$ matrix [8].) The result was a set of energy intensities, similar to economic prices. These intensities were the direct and indirect energy amounts (by type) that moved from the finite resource base per unit of output of each of 400 sectors of the economy, during a given year.
Figure 1. The energy balance for a specific type of energy for the $j$th sector of the economy for a given year. The energy intensities are the $\varepsilon_i$; $E_j$ is the direct energy used in sector $j$. The $x_{ij}$ are the elements of the economic transactions matrix, except that the energy rows are in physical units (British thermal units, BTUs).

The intensities were derived from the energy balance in figure 1, for each energy type.

In figure 1, $E_j$ is one element in a list of the physical amount of energy of a specific type (coal, crude oil, refined petroleum, natural gas, electricity) used by each sector of the industry and commerce, and $\varepsilon_i$ is the $i$th element in the vector of energy intensities of this type (physical units, e.g. BTUs, per dollar) embodied in each of the (non-energy) inputs $x_{ij}$ to sector $j$, summed for the total direct and indirect embodied energy input to this sector. Hence, the I-O analysis method developed by ERG produces the embodied energies. To calculate a total annual physical measure of the energy moving from the natural resource base, ERG combined the coal intensity, the crude petroleum intensity and a portion of the electricity intensity representing the contribution of nuclear and hydropower. To calculate the energy embodied in imports (e.g. Japanese automobiles), ERG assumed that each input had the same inputs as their closest domestic counterpart.

From figure 1, we get, in matrix and vector form,

$$\varepsilon \ast x + E = \varepsilon \ast \hat{X}. \quad (5.1)$$

Solving for $E$ gives, with equation (4.1),

$$E = \varepsilon \ast \hat{X} - \varepsilon \ast A \ast \hat{X}, \quad (5.2)$$

leading to the vector of energy intensities

$$\varepsilon = E \ast \hat{X}^{-1} \ast (I - A)^{-1}$$

or

$$\varepsilon = \epsilon \ast (I - A)^{-1}, \quad (5.3)$$

where $\epsilon = E \ast \hat{X}^{-1}$, the vector of the physical energy of a specific type used directly by each sector per unit of total output of that sector.$^3$ The vector $\epsilon$ and the matrix $A$ are assumed constant for the period of the data, usually a year. The actual calculations were done with a modified approach shown in the appendix.

These intensities were calculated with equation (5.3) using the $A$ equivalent matrix, modified to contain the physical units of energy in the energy sectors for the years 1963, 1972 and 1977 (see appendix). The major effort became the modification of the $A$ matrix to substitute the physical units of energy for the dollar value and to maintain the proper overall energy balance. This took at least two full-time equivalent (FTE) years of effort for each data year.

The bulk of the work conducted by the ERG (1971–1986) focused on the various applications of these intensities to answer questions about the energy conservation potential of the individual sectors of the economy and of individual consumers.$^4$

$^3$The modern, more complex method for calculating the intensity is given in the appendix. ERG used this modern I-O method for all years: 1963, 1967, 1972 and 1977 [7–9].

$^4$The federal support for energy conservation research essentially disappeared in the early 1980s. During the 15 years of energy research by the ERG, a slightly lagged nationwide correlation between availability of federal funding for energy conservation research and energy price rises was noted.
The ERG published more than 200 papers during its short lifetime, most of which found their way into appropriate professional journals. Over the 1970s, the ERG members published 15 articles in Science alone. The team also managed to establish a kind of policy record, perhaps a permanent one, as the only research group to initiate and supply supporting documentation for two (unsuccessful) congressional attempts to establish an energy tax. The ERG had shown that such a tax, placed on the physical energy as it moves from the natural resource base, would produce widespread, effective and equitable energy conservation. These results are discussed below.

One of the most successful efforts of the ERG was the comparison of the energy (combined types) intensities with the labour (total FTE jobs) intensities for a given year. The ERG research showed conclusively that energy and labour are trade-offs, or are substitutes, just as had been shown in the container study. Historical research revealed that, when the price of electricity, for example, rose relative to the average (non-salaried) wage, total energy use decreased and employment increased, per dollar of GDP. In this situation, labour productivity would decline and, eventually, real wages would also decline, all else staying the same.

Folk & Hannon [10] wrote on the trade-off between energy and labour for the 400 sectors of the US economy. The authors determined the labour intensities in a manner similar to the calculation of the energy intensities. They compared the changes in these intensities between two consecutive periods, showing that energy-intensive products are not labour-intensive and vice versa. Economists Bezdek & Hannon [11] wrote on the energy and labour differences between a unit of government spending on interstate highway construction and the alternatives of healthcare, criminal justice and sewage treatment plant construction. All these alternatives required less energy and created more jobs than highway construction. Analysis [12] of a particular county in southern Illinois, where Interstate 57 was being constructed, while a large Corps of Engineers reservoir was also being constructed, revealed no correlation with unemployment there. The major workforce for such construction comes from large cities at great distances just for the weekday work in the county. This result contrasted with the political justification that the highway and reservoir were cures for high county unemployment. These studies were aimed at producing changes in federal spending policy and, in that regard, were a notable failure, despite lengthy testimony by Hannon before state and federal legislatures.

Ford & Hannon [13] completed a study of the effects of a national ceiling insulation programme, a plan for the massive substitution of materials for energy. The plan would have net energy savings of about 0.4 quads. Advantages included not only reductions in BTUs per year but also increased employment of an estimated 25 000 jobs after the additions were finished. They assumed that the programme was an alternative to investing in energy utility expansion. The savings paid off the programme in about 8 years.

Again, despite sharing the results through testimony before Congress on several occasions, the impact of these presentations was difficult to show. The research was continued anyway, with the hope that study results were subtly influencing government policy in unseen ways.

One of the most interesting and politically effective studies of the connections between energy and materials was conducted by ERG post-doc Peter Kakela on the use of low-grade iron ore in iron making [14]. In the USA, iron ore comes primarily from the state of Minnesota, which had long taxed the high-grade ores. Those ores, however, were severely depleted during the war. After the war, low-grade ores were mined and concentrated into a hard, gravel-like material called taconite, before shipment to the steel plants. The taconite companies were granted tax relief due to the added cost of ore refinement. Kakela found that the use of taconite ores so greatly increased the speed of iron production that the cost of iron was lower than when the high-grade ores were used. Total energy use per ton of iron was significantly reduced by the use of the lower-grade ore, dispelling the long-accepted idea that the high-grade ores should be used first. As a result of this paper, taconite taxes in Minnesota were increased substantially.

Broderick & Hannon [15] studied the potential for energy conservation through increased steel recycling. For the industry, the conclusions were bleak. Rising energy prices should not affect increased recycling, because this energy-intensive industry was already well aware of its
energy cost and was maximizing its scrap use. Energy price increases would be passed on to the consumer, resulting in decreased steel demand, thus producing the industry’s only major contribution to energy conservation. The different materials found blended in purchased scrap (e.g. automobile hulks) inhibited an increase in recycling. Electric arc furnaces used 100 per cent scrap, and their energy costs per dollar of steel were about 44 per cent lower than that of steel produced by the basic oxygen process (30% scrap). The steel produced by the electric arc process was generally of lower quality and it readily filled the demands for these types of steel.

Recycling of consumer scrap metals is a twofold problem. First, private scrap yards hoard scrap during times of low demand and reap their profits when demand for steel cannot be met from virgin ores. Scrap prices rise sharply in times of high demand. Second, the steel companies own the virgin ore resources but not the scrap yards. These companies draw first on the virgin ores and, should steel demand be high enough, turn at the margin to the scrap yards.

Gunn & Hannon [16] studied the potential for energy conservation in the paper industry. The research revealed that a period of rising energy costs after 1974 was followed by a jump in paper recycling rates. The maximum rate of recycling was about 40 per cent scrap, but the researchers showed that the economically optimum scrap use level was somewhere between 27 and 31 per cent, the rate in the industry at that time. Both levels reduced the total energy cost of finished paper. Again, ownership by the paper companies of the virgin pulp sources but not of the scrap depots created a bias towards first use of virgin pulp sources.

The volatility of scrap prices is also a deterrent to recycling. Differences between dollar cost of virgin pulp (steady cost, predictable quality) and scrap paper pulp (volatile price, variable quality) and the ever-shortening fibre length due to repeated recycling, all conspire to make the increased use of scrap paper a difficult process.

Working with New York City architect Richard Stein, two graduate students and I developed the energy and labour cost of building construction [17]. Here, the team found a major trade-off between energy and materials. About 20 per cent of the energy cost of a building could be saved mainly by the use of more materials (triple glazing and insulation) and by energy-conservation practice in the input industries but also through material substitution. The first two approaches reduce the lifetime energy cost of the building significantly.

In passing, the research team also pointed out that the fresh-air use rate in buildings that allowed smoking was six times higher than that in buildings that did not. This evidence, along with lower-cost fire insurance and the anti-smoking campaigns, helped to speed the elimination of smoking in buildings.

In a 1975 Science paper, I laid out three dilemmas for the typical person wishing to change their total energy footprint unilaterally [18]. First, national energy conservation can be achieved only by driving up the price of energy, especially electricity relative to wages, and this results in more employment. The increase in employment comes typically at the low-waged end of the spectrum, whereas decreases in employment occur at the high-waged end (as in the drink container example cited earlier). The dilemma comes from the resistance of the high-waged, highly organized employees who can afford to pay high union dues, thereby establishing union policy. At the same time, no support for the change comes from the relatively disorganized low-waged employees. In addition, the jobs lost are those that exist in the electricity-intensive sectors, while the jobs that would be gained do not yet exist. As the rising relative cost of energy spreads throughout the economy, this effect on labour causes labour productivity to decrease (less output per manhour, a reverse of the historical trend of declining energy prices). Inevitably, this decline is associated with a decline in real wages. This effect does not necessarily mean a substantial decline in the GDP of the country. A recent MIT study [19] showed that an emissions tax imposed now that raised $500 billion a year would have a less than 2 per cent negative effect on GDP by 2050. However, this result is not necessarily inconsistent with the expected decline in real wages, because a growing number of people with declining real wages can result in a growth in total personal consumption, and therefore growth in GDP.
The second dilemma comes from the monotonically rising relationship of total direct and indirect energy use and household income noted above: the only way to actually save energy is to reduce income. Even saving money results in energy use through the investment market.

The third dilemma of the person determined to save energy comes from the fact that any voluntary energy-saving effort, such as riding a bus to work rather than driving a car, also saves money. This money savings is then spent on other goods or services, and those require energy (and jobs) to provide. Sometimes, the energy demands of this alternative spending can completely offset the original savings, as when, for example, the dollars saved by shifting from meat to vegetable consumption are spent on gasoline. We called this the ‘savings responding effect’ and it has been rediscovered several times since then and now called the ‘rebound effect’.

In an unpublished study with Ben Gerber, the ERG noted that the Gini coefficient, the measure of the equity of income distribution, in the USA began a reversal of its long move towards perfect equity of income in 1975, when the first impacts of the sudden energy price increases were being sorted out. This decline in equity has now greatly increased. Was historically cheap energy the root support for increased equity?

ERG [20,21] showed how direct and indirect energy use varied with household incomes. From this and further studies, the research team concluded that a tax on all energy [22] as it moves from the resource base was the only equitable way to tax energy. Their results showed that direct household energy use, primarily gasoline and heating fuels, saturated with rising income, while the total direct and indirect energy use was linear with income and rose nearly proportionately with income. The tax revenues would be returned to consumers through a corresponding reduction in income taxes. This was the main ERG contribution. Today, owing to concerns over global warming, the emphasis is on a carbon tax rather than on an energy tax. But such a tax does not tax all energy, whereas an energy tax covers most of the carbon releases to the atmosphere and conserves the basic energy resource. An economic rational alternative is to implement a carbon tax along with the removal of the substantial subsidies for the nuclear industry. Also, as was evident in parts of Europe during the sharp energy price rises in the early 1970s and again in the early 1980s, the tax can be quickly removed and slowly restored to ease the impact of a rare sharp price rise for energy imports.

The final paper of the ERG was a comparison of the total intensities of all the goods produced in the US economy for the 4 years in which the energy I-O models could be constructed: 1963, 1967, 1972 and 1977 [9]. The last 2 years spanned the first sharp rise in energy prices, accompanied by measurable changes in US energy use. The research team calculated the reasons for the change in the energy content of the average GNP dollar, a kind of overall energy efficiency measure of the economy. The basic categories were: technological change, market basket change and distributional change. The first is the change in the energy intensities; the second is the change in the distribution of products produced for final demand; and the last is the change among the categories of final demand (personal consumption, government purchases, new capital formation, net exports and inventory change). The change in the energy intensities is found to be the most explanatory of the overall efficiency change of the economy.

6. Dealing with scarcity

One elementary objective of any materials policy would be the determination of the degree of scarcity for the list of materials. Those materials ranked high in this list should be the first to be analysed. Two questions arise: What time series should be watched and analysed for signs of increasing scarcity? What should be the sustainable pricing mechanism?

The search for the appropriate resource scarcity indicators is a long and controversial one. In their influential book, Barnett & Morse [23] believed in the unlimited cleverness of humankind to find substitutes for whatever resource was becoming scarce. Barnett & Morse based their argument on the decline over time in direct labour required to bring many different resources into the economy. Sufficient objection arose over the following decades, culminating in a book that was aimed to specifically counter their argument. Most of the authors opposed their result [24].
The general conclusion of these authors was summarized by Fisher [25], who derived the auction price (marginal cost of extraction plus the scarcity rent) as the most appropriate time series from which to detect growing scarcity of a natural resource. The scarcity rent is the present value that a competitive resource extractor will require in addition to his marginal cost of extraction, in order to compensate him for those future times when the resource has been depleted. The scarcity rent should grow as the resource is depleted. Resource producers will add a scarcity rent to the resource’s marginal cost unless their government decides otherwise (e.g. the decision to nationalize the natural resource). The government would most likely, owing to political pressure, then charge marginal cost as the price and lose the critical scarcity rent signal. Therefore, economists are right that the market could control the transition to a lower energy and materials use level. However, there are so many subsidies, depreciation and tax relief schedules that the appropriate signal of rising scarcity rent is masked.

An alternative would be to let the current system of pricing stand and to tax materials used to produce the market forces that would enhance conservation and substitution. The quest would then be to find a sustainable materials pricing procedure.

A sustainable resource pricing strategy was first proposed by Ise [26]. He suggested that non-renewable resources should be priced equal to or greater than that of their nearest renewable substitute. This is remarkable foresight. Imagine the level of wind and photovoltaic electricity generation that would be available today if society had started on such an energy path in Ise’s time. Solar energy, captured in biomass or captured in photovoltaics, provides a possible backstop price for energy, under an Ise-type programme.

Wood and stone, however, are unsuitable substitutes for steel and aluminium. When no possible renewable resource exists, the price of the most readily available sustainable source is the price to set on the critical material. This is called the backstop price. For example, suppose (without reference to reality) that vanadium was found to become increasingly scarce and there was no apparent substitute source for it other than from seawater at very low concentrations. The cost to remove vanadium from seawater would be the price to set on the use of the current vanadium stock. This price sends the best signal the market can manage to muster. This price signal might not induce the discovery of new sources of vanadium or a suitable substitute material. However, it would very likely induce the development of an alternative technology to produce the effect of the original vanadium-rich technology.

Setting taxes set to mimic these renewable or backstop prices is a problem. What if the political will is insufficient to establish these prices?

This discussion suggests that, even if the conservation-inducing market prices could be established somehow, or even if appropriate taxes could be put on materials use, or even if neither of these outcomes could be achieved, additional research must be conducted in three key areas: the causes of materials use changes, the impacts on household incomes, and the impacts on employment and energy use. Such studies show the advantages and disadvantages of the oncoming materials scarcity. They are the last resort, early-warning devices of scarcity. They acquaint the government and the people with the issues of scarcity. It is the filtering of such research by governments and their populations that is the test as to whether or not a democracy can thrive in the time of scarcity of fundamental resources. And such studies would underpin the development of coherent national energy, materials and employment policies. Such policies now seem to be at crossed purposes. For example, implementing an energy conservation policy might induce certain material scarcities. The employment policy that supports a thrust for higher wages undercuts the move to substitute more labour-intensive processes for less energy-intensive ones.

This review of the historical research conducted by the ERG on energy use in the economy hopefully offers insight and ideas for expanding the research programme for materials conservation today. Following are more definitive suggestions.

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5A possibly suitable definition of renewable resources are those that are flow based, stemming from solar flow.
7. The change in materials use

(a) Isolating the causes

Materials flow $M$ could be assigned to population size $P$, to income $G$ (GDP, $ per capita) and to technological change, $T$ (material flow per GDP$). The change in material flows (the delta forms) between two periods is approximated by three weighted changes in $P, G$ and $T$ (cross $\Delta s$ deleted):

$$\Delta M \approx T \ast G \ast \Delta P + T \ast P \ast \Delta G + P \ast G \ast \Delta T. \quad (7.1)$$

With the known series of $P, T$ and $G$ and the changes in each, the reason for the change in use of any particular material can be assigned to each factor. This could narrow the investigation for conservation policies for that material.

Another means to assign material flows to cause is to define the change in material use efficiency: $M$ per dollar of $G$ [9]. The ratio can be defined for a particular material as

$$\frac{M}{G} = \sum_i \sum_j S_{ij} S_i, \quad (7.2)$$

where $S_{ij}$ is product $i$’s share of final demand category $j$ and $S_i$ is $j$’s fraction of $G$. The change in $M/G$ can then be decomposed into three parts:

$$\Delta \left( \frac{M}{G} \right) \approx \sum_i \sum_j (\Delta c_i S_{ij} S_j + \Delta S_{ij} c_i S_j + \Delta S_i c_i S_{ij}), \quad (7.3)$$

where $c_i$ is the total intensity of the material of concern, derived from (A1).

The first term in equation (7.3) is the technological change, the middle term is the market basket change (the variation in final demand due to product use variations) and the last term is called the distributional change (the variation in amount of GDP in each of its categories). This breakdown of the causes in the material/GDP ratio allows the researcher to isolate the importance of technical change between the periods of I-O tabulation from changes in distributions within final demand. For instance, consumer reaction to rising embodied aluminium costs could be isolated from shifts between total consumer spending and government spending. With this information, researchers can begin to further isolate the reasons within industrial and commercial production techniques that cause the growth or decline in use of the material of concern.

(b) Calculating the total material intensities

Equations (7.2) and (7.3) cannot be executed without the transformation of the basic I-O matrices to include the physical flows in the appropriate rows of the $x$ matrix of equation (4.1), for two separate periods. Then, the material intensities can be calculated for each period. They form the basis of the entire set of comparisons that could be made, as was conducted by the ERG. The actual calculations should be performed with the equations in the appendix, with the appropriate vectors of material flows measured in physical units. This use of physical units of the material of concern is required because of the great variation in price paid for the material across the industrial commercial spectrum. This variation is caused by differences in local and federal regulations, in subsidies, in depreciation rules and in tax levels.

The materials conservation policy should include the analysis of the materials industries themselves and the intensive materials-using industries, the final demand commodity and type variations, and the materials intensity of household consumption. Only a probe of the full range of viewpoints will show the points of most efficient policy prescription.

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6 Please keep in mind that, although equations are provided in the text, use of the newer I-O theory described in the appendix is advised.
Once the basic I-O framework is constructed and applied to several industries, it becomes the platform for the analysis of various possible materials conservation policies. One policy that is parallel to the best policy the ERG could suggest would be a tax on the scarce material at the point where it emerges from nature. Alternatively, an equivalent cap and trade policy could be implemented with equal effectiveness. Permits to use a certain amount of a particular material (the overall use is set as the cap) can be auctioned among potential users. The proceeds from the tax or the auction can be redistributed to ensure an equitable impact on consumers and/or to promote technologies that use that material more effectively. The efficiency of the auction can be assured by allowing the buyers to trade the permits to the point where a market in the permits is established. The USA has a successful cap and trade policy on sulfur dioxide emissions.

The three dilemmas of rising energy scarcity laid out in a 1975 Science article [18] must be addressed for the materials conservation programme. Are materials and labour substitutes or complements in the overall economy? If they are substitutes, will rising scarcity of a particular material increase employment and, if so, what happens to the wage structure?

The development of a set of materials intensities allows policymakers to determine the material demands behind various household expenditures. How much of a certain material does the above-average-income household use directly and indirectly compared with a modest-income household? How did the change in technology, market basket and distribution of final demand in a given period of time affect the demand for that material, and what was the associated change in energy use and employment? What is the equity impact of the rising price of scarce materials? What is the substitution potential in material-intensive industries of a scarce material by a more plentiful one? What is the effect on total energy use and total employment of policies that induce such substitutions? What would be the impact on material use, energy and employment if recycling of that material were increased substantially? What need for the development of new production and use technologies is suggested by the research results?

Finally, in the anticipation of materials scarcity, will pre-emptive conservation by industry and commerce save them money? If so, what are the ultimate materials, energy and employment use changes when that saving is spent on other products and services?

The goal, of course, is the development of a clear national (if not international) materials use policy, one that is consistent and coherent with similar energy and employment policies.

(c) Combining economic and ecological systems

Engineers hold the ability to develop new technologies in high regard. As shown by earlier examples, the benefits of such accomplishments will not be useful if socio-economic impacts are left out of proposals. An additional impact to consider is impact on the ecosystem. The most relevant research, then, will include the assessment of the socio-economic–ecological impact of technological materials conservation policies.

First, a comparison of the definition of stocks and flows is needed. In the ecosystem, the stocks of biomass are the capital goods, and the energy flow is sunlight. The fossil fuels are escaped biomass, those bits of organic material collected through the millennia in anaerobic spaces. The apparent goal of the ecosystem is to convert a maximum amount of sunlight into biomass and return this captured energy back to the environment in the highest possible entropy state. The mature ecosystem is characterized by spatially and chemically tight recycling. The goal appears therefore to be one of efficiency of conversion of low-entropy flow to high-entropy ones, with the result of a stable, sustainable system. Modern society’s definitions of stock are somewhat different and our apparent goals are different as well. We, too, generate a great deal of high entropy but we do not dwell so much on the efficiency of that conversion. We subsume the ecosystem into a fragile agriculture and tap the fossil fuels as fast as possible. We also uniquely tap the low-entropy gifts of planet formation—those of ore concentrations, radioactive materials and geothermal energy—again without an emphasis on efficiency, stability or sustainability. Perhaps with the aid of a combined I-O approach, we can begin to resolve these differences for the benefit of both systems.
Hannon [27] developed an I-O framework for the ecosystem where the net output (the GDP of the ecosystem) was its net exports, inventory change, respiration and new biocapital formation. Respiration was analogous with household and government consumption of the economic definition. The idea was applied to a specific ecosystem to show the direct and indirect energy dependence of the top carnivore on the solar input to the system. Ulanowicz, Costanza and I showed how such a matrix approach to ecosystem studies provided a useful framework to collect the data from many different ecological research projects [28]. Such a framework could be used to show the direct and indirect connections of the various biological elements of the system. For example, if fishing were performed on a system, the framework could show where and how much was needed to compensate and stabilize the system [29]. I showed that these ecological energy intensities played the role of prices when one took such a view of the ecosystem [29]. Extending the economic analogy further into ecology, I showed how an ecological discount rate could be calculated; this could be thought of as nature’s time preference rate [30]. Under the proper conditions, the natural discount rate of an individual or a species can be approximated by its rate of respiration energy—the rate of heat release—per unit of biomass energy. Metabolic data revealed that the smaller individuals have a higher discount rate than larger ones, and males a higher one than females of the same size. The discount rate should drop as the individual ages and as the species evolves. These natural discount rates capture both the idea of the inevitable entropy creation of living organisms and the duration of captured energy in their biomass. In this sense, the natural discount rate is a measure of the value that a specific unit of biomass (biocapital) has to its ecosystem.

Working with ecologists has its benefits. As an amateur, I had often asked: Is the ecosystem in chaos all the time or are the flows and stocks steady? If the system were thought to be chaotic, calamitous, then humans might well assume the right to conform to our will. If the system has steady flows and stocks, it is balanced, efficient, sustainable, and we should be reluctant to tamper with it. It turns out that the answer depends on one’s point of view. If you examine a patch of forest or a prairie for a long enough time, the system matures and burns down, leading the observer to think the system is chaotic. On the other hand, if one examines an adjoining collection
Table 1. The input–output accounting relationship for the combined economy and ecosystem. The net input row is a source of prices that allow the net output, naturally accounted for in different units of measure, to be made commensurate, resulting in a gross system product (GSP), analogous to the GNP for the economy alone. Because some irreplaceable and irrecoverable flows occurred (open physical system), the GSP ($2371) is less than the evaluated net input ($2440).

<table>
<thead>
<tr>
<th>economic sectors</th>
<th>prod.</th>
<th>serv.</th>
<th>min.</th>
<th>anim.</th>
<th>veget.</th>
<th>net export</th>
<th>new capital</th>
<th>total, r</th>
<th>capital lost</th>
<th>(row sum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>production</td>
<td>15 000</td>
<td>900</td>
<td>700</td>
<td>500</td>
<td>500</td>
<td>1000</td>
<td>1000</td>
<td>2000</td>
<td>0</td>
<td>19 600</td>
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<tr>
<td>services</td>
<td>8000</td>
<td>2000</td>
<td>100</td>
<td>200</td>
<td>500</td>
<td>50</td>
<td>0</td>
<td>50</td>
<td>100</td>
<td>10 950</td>
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<tr>
<td>minerals</td>
<td>5000</td>
<td>0</td>
<td>0</td>
<td>1000</td>
<td>-1000</td>
<td>0</td>
<td>0</td>
<td>-1000</td>
<td>200</td>
<td>5200</td>
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<tr>
<td>ecological sectors</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>animal</td>
<td>500</td>
<td>0</td>
<td>100</td>
<td>1000</td>
<td>0</td>
<td>-100</td>
<td>200</td>
<td>100</td>
<td>0</td>
<td>1700</td>
</tr>
<tr>
<td>vegetative</td>
<td>1600</td>
<td>600</td>
<td>0</td>
<td>2000</td>
<td>0</td>
<td>0</td>
<td>50</td>
<td>1200</td>
<td>1250</td>
<td>5450</td>
</tr>
<tr>
<td>net input</td>
<td>1000</td>
<td>300</td>
<td>400</td>
<td>18 000</td>
<td>20 000</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>biocapital</td>
<td>1800</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>panel values</td>
<td>3.0</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
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<tr>
<td>biocapital ($)</td>
<td>540</td>
<td>200</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>net input ($)</td>
<td>1000</td>
<td>300</td>
<td>400</td>
<td>540</td>
<td>200</td>
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<td></td>
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<tr>
<td>price, ε</td>
<td>1.083</td>
<td>0.156</td>
<td>0.267</td>
<td>2.159</td>
<td>0.199</td>
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</tbody>
</table>

The key requirement of such a scheme is to determine the economic value of the respiration quantities for each species in the ecosystem. These values would have to come from a panel specially arranged for this purpose. These values allow the net input vector to the combined system to be expressed entirely in monetary terms. The system prices can then be calculated by equation (5.3). These prices can be multiplied by the net output vector to find the value of the gross system product (GSP value = $2371 in table 1). Because the net output sum does not contain the lost capital values of each economic and ecological sector, the GSP value is less than the value of the net inputs ($2440 in table 1). With these two values, the efficiency of the overall system can be calculated (97% in table 1).

The work of the ERG at the University of Illinois at Urbana-Champaign provided one of the foundation stones of the now-flourishing International Society of Ecological Economics. The modification of the I-O economic theory allowed it to be fruitfully used in the analysis of natural resource flow in both economic and ecological systems. The analysis has not only provided a common framework but also brought a consistent physical basis to both systems. It
has clarified and identified the definitions of the net outputs and net inputs so that both systems can be combined into a single analytic framework, such that no flows in either system are omitted or double counted. Although the specific numerical results of this work are dated, the process by which the analysis was conducted creates at least a suggestion for future analysis in the arena of materials research.

Although I started this work in 1969 with several students, the research really began to blossom in the early 1970s when Clark Bullard and Robert Herendeen joined the group and a bit later when Michael Rieber arrived. Hugh Folk was a close colleague. Each member took his or her own path in this emerging field but resided on the same floor of the same building. We could then maintain that exquisite balance between own-career and group research effort, so essential at a modern university. Some of our many students and post-doctorates stand out in memory now: Peter Fox-Penner, Tony Sebald, Tim Gunn, Robert Costanza, Matthias Ruth, Cutler Cleveland, Charlotte Ford, Tom Blazek, Steve Casler, Peter Kakela and others all doing well in their own fields. I also owe much to Tina Prow and John Abelson for their many helpful editing comments. The author apologizes for the unseemly amount of self-reference in this paper. It reflects the excitement stemming from the ERG efforts throughout the 1970s with the production of nearly 300 papers and technical memos: we were able to investigate energy conservation and mathematical systems ecology when they were emerging new fields, ripe for enquiry. Most of the applications of the I-O theory and the work in combining the economy and the ecosystem were published by the author either alone or with his colleagues and students. Although most of the work was performed almost 40 years ago, it is hoped that the methods continue to be relevant and can contribute to the important area of materials efficiency and conservation.

Appendix

Since the 1960s, the Leontief transactions matrix has been officially replaced by a set of matrices, each derived from the same industrial census data. The problem with the original theory is that an industry produces multiple commodities, but the matrix A is made from the exchange between whole industries. The new matrices are U, an m commodities by n industries Use matrix and V, an n by m Make matrix. As the names imply, U is a description of which commodities are used by which industry and V describes which industry makes which products. The physical amounts of energy use were substituted for their energy-dollar amounts in the rows of U.

The term \( \hat{g} \) is the diagonalized vector of the n total industrial outputs. The term \( \hat{q} \) is the diagonalized vector of the m total commodity outputs. Then, it can be shown [7] that

\[
\varepsilon = e(I - BD)^{-1},
\]

where \( e \) is total energy intensity of type i needed to make a unit of commodity j, and e is an \( m \times n \) matrix with a 1 in the energy row for an energy commodity and 0 otherwise, and \( B = U\hat{g}^{-1} \) and \( D = V\hat{q}^{-1} \) with BD a commodity-by-commodity normalized exchange matrix, the substitute matrix for A in the theory presented in the text. Matrices B and D are assumed constant for the period of the data, usually a year.

The total primary energy intensity was a very particular sum of the coal, crude petroleum and natural gas, and refined petroleum and natural gas intensities [7], with hydro and nuclear energy electricity assumed to be made from a standard fossil-fuelled power plant.

The text here uses the original Leontief framework, as the explanations are simpler. The ERG total energy intensity calculations were based on the equation in this appendix, with the energy commodities represented in U by their physical rather than their dollar flows for all US Bureau of Economic Analysis years. This same process could be used for the critical material commodities.

Labour intensities, whether of total employment or for each occupation, are formed by changing the vector e to the employment, either total full-time equivalent jobs or those of a particular occupation, per unit of commodity output. These intensities are also assumed to be constant for the data period. Unlike materials and energy, labour is not a part of the Use or Make matrices. It is defined as a part of the external input to the economy.
More recent work in mixed units I-O research [32] confirms the methods used in the ERG approach, now nearly 40 years ago. They are applied to the materials flow part of the economy rather than the energy flow used by ERG, and consequently should be of great value in evaluating materials conservation and the total efficiency of their use.

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