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# Foreword

Energy and environment have been continuing themes at IIASA since the Institute began operation over sixteen years ago. The relevance of energy technology to environmental concerns has become increasingly evident with the emergence of *acid rain* as a high priority issue in both Europe and North America a few years ago and, more recently, the possibility of a global warming via the so-called *greenhouse effect.* The focus on energy as a criticial element in the equation has become ever more intense as the conflict between economic development of the "third world" and environmental protection for the "first world" has seemingly shifted from the potential to the actual.

This paper addresses that apparent conflict. It points out that most past studies of the potential for energy conservation have assumed much higher levels of energy-use efficiency than is really justified, with correspondingly pessimistic implications about the potential for future gains. Thus, in one respect, the paper is profoundly optimistic. On the other hand, it points out some of the institutional barriers that need to be overcome before energy conservation becomes a serious alternative to supply-oriented strategies.

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# Abstract

It is argued that the US is much less efficient at converting energy into useful final goods and services than has generally been assumed. Defining efficiency as the ratio of theoretical minimum energy consumption to actual energy consumption, for essentially the same mix of goods and services we have now, the current level of energy efficiency for the US is about 2.5% plus or minus 1%. This implies that energy efficiency for the nation *as a whole* could be increased tenfold without exceeding efficiency levels currently claimed for internal combustion engines. Conversely, it means that GNP could increase by a factor of ten without using more energy than the US now consumes. It also implies that a sufficiently strong combination of policies to encourage energy conservation technology worldwide would permit accelerated economic development in the third world without further global environmental degradation.

# Contents

# Energy Inefficiency in the US Economy: A New Case for Conservation

## 1. The Fundamental Misconception

Once again, energy is in the news. The worldwide climatic warming attributable to carbon dioxide emissions from the combustion of fossil fuels is a cause for concern. Supply-siders see it as another chance for nuclear power. For instance, the chief scientist of the Department of Transportation calls it "the only realistic, abundant, economic and widely accepted energy source that produces no greenhouse effect" (Singer, 1988). Underlying this argument is a fundamental misconception. It is widely assumed by engineers, businessmen, government leaders, and well-informed citizens alike that economic growth and energy consumption are inseparable. More specifically, it is assumed (1) that there is a minimum energy input requirement per unit of GNP and (2) that we are already rather close to that minimum. In other words, it is assumed by most people (without much analysis) that we are using energy almost as efficiently as is technically possible.

If these assumptions were true, economic growth would necessarily be strictly proportional to energy consumption growth. By the same token, any reduction in the supply of energy would have to be translated into an economic decline. Evidently, if the economy really did use energy as efficiently as possible, or nearly so, then the energy-economy link would indeed have to be extremely tight. Under these circumstances the potential for conservation would necessarily be correspondingly limited.

Contrary to this prevailing view, I contend there is *no* absolute minimum energy input requirement to produce a unit of economic value (GNP), beyond the small amount required to sustain human metabolism itself. Even if we insist (without any particular justification for doing so) that the present mix of services is *optimum*, and that the basic technologies for delivering final services such as houses and cars cannot be improved upon, these services could, in principle, be produced with a very small fraction of the amount of energy actually used at present in the USA. In fact, the necessary energy is probably no more than would be available from wind, hydro-electricity, solar power, recycling waste agricultural biomass, and other renewable sources.

In the following I use the term "efficiency" in the physical sense. (Economic efficiency is related to physical efficiency, but not in a simple way.) Hereafter, "energy efficiency" is always taken to be a ratio, of which the numerator is *the least possible energy required* for a given function, while the denominator is *the actual amount of energy consumed* to perform that function. At this point a couple of caveats need to be stated explicitly. First, in estimating the minimum possible energy use for a function (for instance, personal transportation) I assume, as given, the familiar modal categories such as automobiles, buses, and aircraft. I assume, also, that we want them to continue to *look* and perform much as they now do. Similarly, I assume that houses and household appliances will continue to be configured much as the current models are. These assumptions are for convenience, of course, but they provide a useful baseline. It is likely that, in the very long run, generalized services such as *shelter* and *communications* might be accomplished by other, more radical means, requiring far less energy, but no attempt is made in this paper to reflect that possibility. This bias results in an overestimate of the current overall efficiency of energy use.

The second important caveat is that conventional thermodynamic analysis systematically underestimates the true efficiency of most machines and processes by taking as the *theoretical* limit the energy that would be required if all processes were reversible and carried out at infinitesimal rates. It is well-known that in the *real* world time has value, which is another way of saying that the *rate* of output of an energy conversion device (i.e., its power output) is likely to be as important as (or more important than) its thermal efficiency. There is an unavoidable tradeoff between energy and time. [This point has been particularly stressed by Weinberg (1977, 1978, 1980, and 1982).] The design point for optimal power output is not the same as the design point for optimal thermal efficiency. Moreover, since real machines can only be made of real materials, with finite heat conductivities – additional constraints – current engine and process designs are much closer to achievable limits than is sometimes realized.[1] This bias tends to compensate for the previous one, by underestimating the current efficiency of unit operations and unit processes.

Subject to the above caveats, I estimate the current energy efficiency of the US economy at present to be about 2.5%, give or take 1%.[2] Greater precision is difficult to achieve because the calculations involve some estimates where there is no reliable published data. Nevertheless, despite the *fuzziness* of the number, it is more than an order of magnitude smaller than the (roughly) 50% figure that has been used explicitly in many influential studies (and implicitly in most others).[3] For example, see *Figure 1.* Even in sophisticated studies, e.g., Dunkerley (1980), *useful energy* is typically calculated by (1) subtracting energy lost in converting energy from raw form to whatever form it is delivered to its point of consumption, and (2) applying *coefficients of thermal efficiency* taken from a standard source such as Nordhaus (1975). These coefficients, of dubious parentage to begin with, have been widely misused, as will be seen.

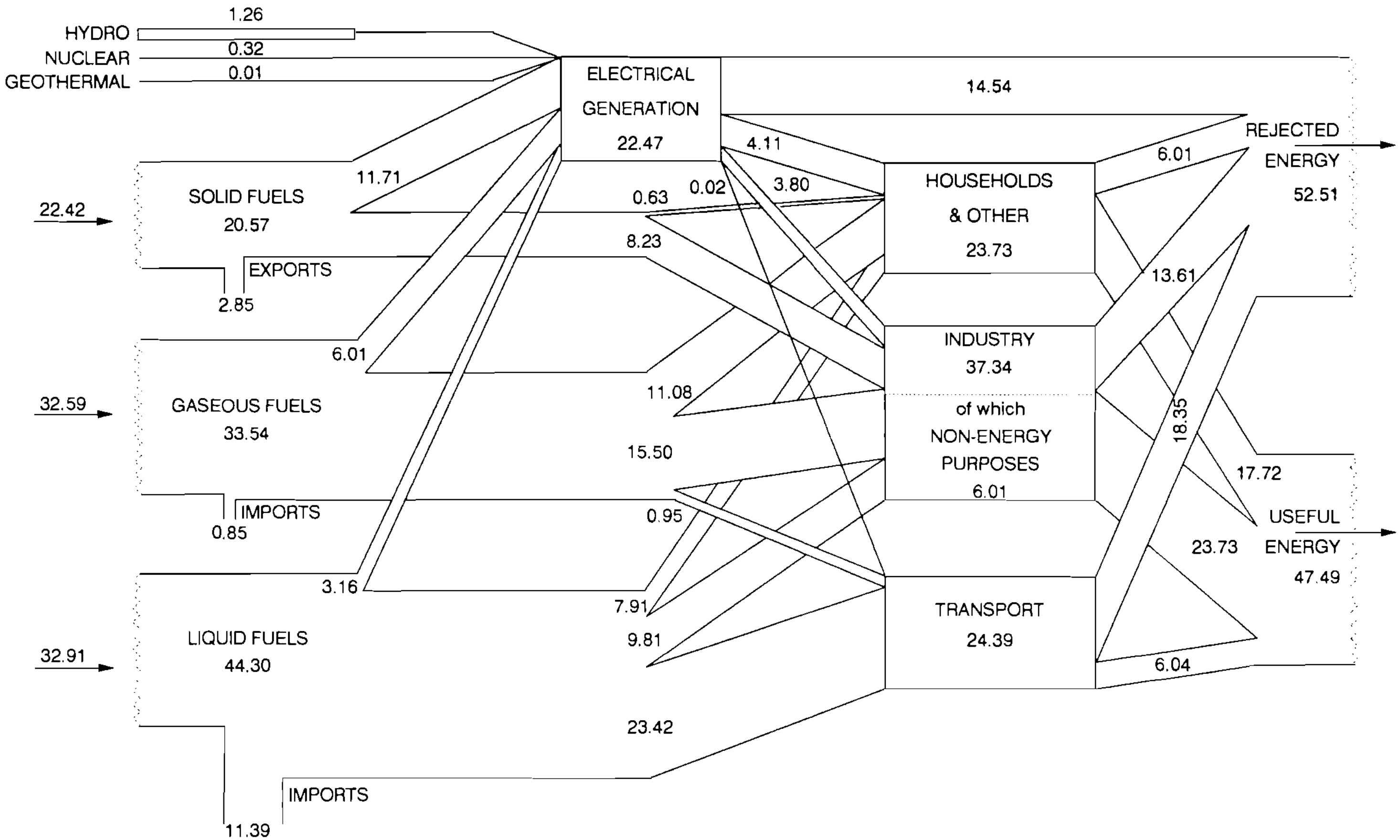


*Figure 1.* **Energy flow in the USA – actual 1970 percentages. (Source: Bridges, 1973.)**

Implicit confusion of energy *delivered* to a final user with energy actually needed to perform a final service is more insidious and more widespread. It leads naturally to an assumption that the long run price elasticity of energy demand is low, consistent with an unstated assumption that opportunities for energy conservation are limited to the energy conversion and delivery functions. If this assumption were true it must follow that there is a minimum quantity of energy associated with each final service, and therefore a lower limit on the energy/GNP ratio. The majority of energy demand forecasts in recent years reflect this basic misconception and its implication that conservation "can only nibble at" the problem.[4] This implication must be rejected, not only on theoretical grounds, but in the light of recent experience.

It is the tendency to confuse delivered energy with needed energy that encourages most scientists and engineers to assume that the potential for energy conservation is smaller than it really is. This may be because even small increases in the energy efficiency of steam turbines or jet engines (without sacrificing power) are now getting very hard to achieve, given the limitations of real materials and the tradeoffs and constraints associated with *finite time/finite rate* operation. The once highly touted programs like magneto-hydrodynamic (MHD) power generation have fallen by the wayside, but the ceramic turbine remains on the drawing boards.

It is perhaps natural to assume that opportunities for increasing efficiency must be equally scarce and costly elsewhere in the economic system. However, natural or not, this assumption is unjustified. Indeed, fairly spectacular increases in the energy efficiency of the US economy as a whole have evidently occurred over the last fifteen years *without* significant improvements in the efficiency of unit operations, *viz.* steam turbines, jet engines and so on.[5]

The critical question for public policy is: can we depend on energy conservation as a substitute for growth in the energy supply? If so, for how long? I argue that the answer is yes, for several decades at least. In short, the energy/GNP ratio can decline for a long time to come. The only real question (a serious one) is how quickly we can recognize and begin to dismantle a policy-edifice, decades in the building, that has distorted market incentives, encouraged profligate energy consumption and discouraged investment in energy-conserving technologies.

## 2. How Energy-Efficient is the US Economy?

To address this question realistically, it is helpful to view the economic system as a sequence of transformations, beginning with raw materials extracted from the environment and ending as wastes returned thence. At each stage of the production process energy is used, as materials are separated, purified, alloyed, shaped, assembled into products or systems, and operated to deliver services. (Energy is not actually lost, but it becomes thermodynamically unavailable.) *Figure 2* indicates the main energy flows and transformations in the economic system respectively. The overall efficiency calculation requires two categories of questions to be answered. The first is how much energy is actually utilized at each stage as

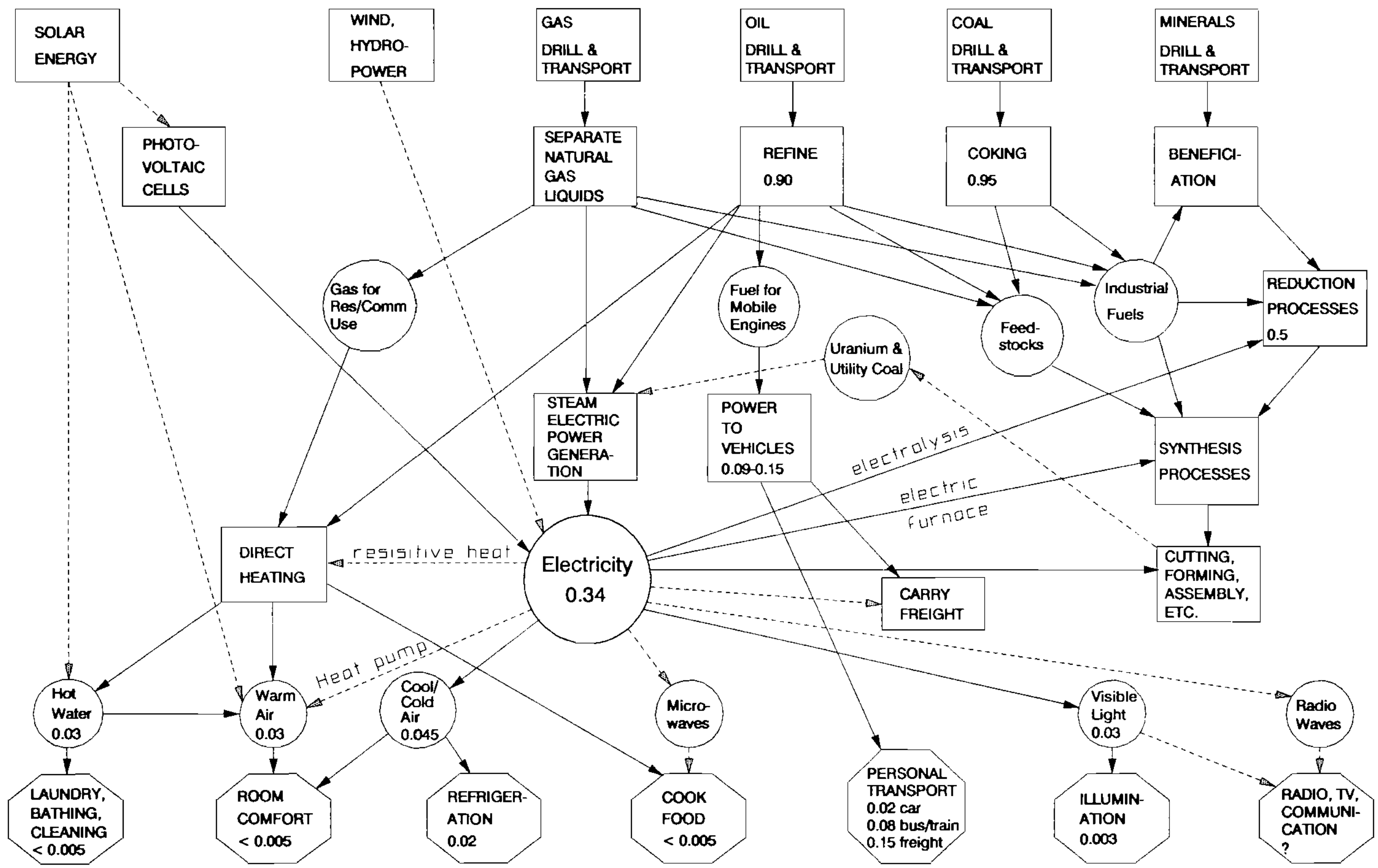


*Figure 2.* Energy transformed to final services.

the system functions today? The second is what is the *minimum* amount of energy that would be required to accomplish the same transformation or conversion – or to perform the same function – in an ideal, reversible, no-loss world? As stated already, the ratio of the second number to the first is the net efficiency, subject to the two caveats previously noted.

The major problem with the better known past estimates (such as the ones cited above) is that they have typically considered only the efficiency of energy delivery. In practice, this comprises the first two conversion stages, *viz.* fuel combustion and electricity generation. The incompleteness of the analysis is compounded by the fact that analysts have frequently used inconsistent or misleading measures of efficiency, especially in regard to heating and cooling.

In many engineering publications that refer to the *efficiency* of heating systems, for example, the term refers to the percentage of the chemical energy in the fuel that is converted into heat and delivered to the walls of the furnace (the hot side of a heat-exchanger). This method of measuring heating efficiency is sanctified in the gas industry, but it is misleading in the extreme. The purpose of a furnace is not to heat the furnace walls, but to heat the room. The major losses in heating systems occur in the process of delivery from furnace to room. If one cares about using as little fuel as possible to deliver a given amount of warm air to the point of use, then efficiency has to be measured differently. The fact that 70% of the energy available in the fuel is delivered as heat to the furnace walls at 1000°F is essentially irrelevant if the heat is wanted in the room as warm air at 70°F.

There are several ways of converting heat at 1000°F into heat at 70°F other than by simply mixing hot air with cold air. For example, one could use the high temperature heat to operate a heat engine, yielding useful work (which could be used to generate electricity), while using the *waste* heat to warm the room. The efficiency of this scheme would be limited by the Carnot cycle efficiency, which depends on the ratio of the (absolute) temperatures of the high and low temperature reservoirs. However, the question at the moment is not which is the most efficient technical scheme, but, rather, what is the least amount of chemical energy in the form of fuel that could supply a given amount of warm air?

The calculation is not difficult once it is correctly formulated. This has been done, for example, by a group of physicists in a summer study on technical aspects of efficient energy utilization, sponsored by the American Physical Society (APS) (Ross *et al.*, 1975). They idealized the task of delivering heat to the room as follows: "The heating system may be conceived to transfer heat from an ambient heat reservoir (at the temperature of outside air) to a reservoir at the temperature of the interior of the house (about 70°F)." Allowing for heating and humidification of infiltrated air (needed for ventilation) the calculated *second law* efficiency turns out to be 2.8%, assuming a *furnace efficiency*, in the sense noted earlier, of 70%. In actual fact, most residential heating furnaces are not nearly this good. [Typical natural-gas fired water heaters are only 48% efficient at delivery heat to the boiler (as compared to over 97% for the latest models (ACEEE, 1984).]

As a matter of interest, the APS Summer Study cited above calculated the following efficiencies for other important domestic and commercial heating and cooling processes (Ross *et al.*, 1975).

| | |
|---|---|
| Hot water heating, electric | 1.5% |
| Hot water heating, gas | 2.9% |
| Air conditioning, electric | 4.5% |

Obviously these figures are much lower than the 70% cited, for example, by the Joint Committee on Atomic Energy (JCAE). To that extent they give a much more accurate picture of the potential for energy conservation. (Apart from the APS study, others that have used more realistic figures include Ayres and Narkus-Kramer, 1976; Krause, 1981; Sorenson, 1982; Olivier *et al.*, 1983; and Robinson, 1987.) But the above figures are still a gross overestimate of the efficiency with which rooms are heated or cooled, as will be seen later.

It is not possible in a relatively short paper to present a complete analysis of all the significant uses of energy. A few representative calculations will have to suffice to make the main point.

## 2.1. Residential and commercial (R&C)

In 1979, the last year for which a complete breakdown of US energy uses has been compiled (see Appendix A), this sector accounted for about 32% of all energy consumed in the USA. Space heating alone accounts for 13.3% of the total (42% of R&C). The very low efficiency of conventional methods for delivering warm or cool air (and providing hot water) have been noted already. The 3% energy-delivery efficiency that is characteristic of current average practice could, in a well-designed system using electric heat pumps, be raised eventually to something closer to 10%, or even more.[6]

But this is still misleading, because we have not yet considered the quantity of heat actually delivered to rooms as compared to the minimum amount needed to make people comfortable. In fact, the amount of heat needed depends on the rate at which it is lost, or on the efficiency with which heat is retained in the room. In short, it depends on the insulation and ventilation. This is quite independent of the calculation of delivery efficiency above. A drafty, poorly insulated room will require a lot of heat to replace the losses, even if it is delivered efficiently. By the same token, a very well insulated room will require very little heat to be delivered at the radiator, regardless of how inefficiently it is supplied. In this context, it should be noted that the major savings in energy for *space heating* in the USA over the past fifteen years have come about almost entirely from improved insulation, not from more efficient furnaces.

How efficiently do we insulate our buildings? So-called *super-insulated* houses, now commercially available – for instance the Northern Energy Home, offered in the northeastern USA – cut heating costs from an average of US$400/year to US$50/year in the New York City area (Goldemberg, 1987). With insulation this efficient, central heating is not necessary and much cheaper electric room heaters can be utilized. Similarly, in recent years a *typical*

Canadian house cost US$80,000 to build and US$800/year to heat (ACEEE, 1984). Thus, by investing an additional in thermal insulation and reducing unwanted air-leakage, heating costs can be cut by seven-eights.[7] By this standard the "typical" US or Canadian house is evidently *no more* than 12–13% efficient, in terms of thermal engineering, as compared with the ideal. If the average efficiency of insulation is 12%, more or less, and the average efficiency of air-heating is 3%, the overall efficiency of energy use for space-heating must be less than 0.4%.

This is still an over-estimate, because it neglects other avoidable losses. For instance, further energy savings would result if heat (or air-conditioning) were only provided in occupied rooms. The inefficiency of heating or cooling empty rooms is obvious.[8]

From a number of studies and actual demonstrations in many countries, it is now clear that virtually *all* use of commercial fuels for this purpose can be eliminated in a properly designed and insulated house, simply by making use of the solar heating available through windows and the waste heat generated by electrical appliances such as the refrigerator. (By making use of improved insulation and heat-recovery, a number of newer high-rise office buildings in the USA, Canada, and Sweden now operate with no heating system at all.) Such a house may or may not cost slightly more to build than a *conventional* house, but it would also cost less to operate. Extra costs for wall and window insulation may actually be balanced by savings in furnaces, air-conditioning equipment and ductwork.[9] The trade-off between capital and operating costs is one that public policy can influence, as will be pointed out later.

## 2.2. Air-cooling and refrigeration

Air-cooling (A/C) and refrigeration account for 3.6% and 2.4% respectively of total energy consumed in the USA (19.4% of R&C). The APS Summer Study (Ross *et al.*, 1975) estimated the overall energy efficiency of conventional air cooling and refrigeration systems as 5% and 4% respectively. Improvements of 17% for room A/Cs and 25% for central A/C units have been reported since 1972 (ACEEE, 1984), bringing the average efficiency of cooling up to around 6%.[10] Again, the *amount* of cooling required is a function of overall thermal insulation and system design of the house. In a new well-insulated building making use of roof overhangs, reflective windows, shades, and other devices to minimize unwanted heat inputs in hot weather, the need for air-conditioning can be reduced by two-thirds or more.[11] Obviously, fixing existing buildings is more costly, but substantial improvements are still possible. If buildings are as inefficiently insulated with respect to cooling as they are with respect to heating (say 12%), we get an overall estimate of 0.7%, again without taking into account the "empty room" factor.

Refrigerators have become considerably more efficient in the decade since the APS study, but exact figures are lacking. The average US refrigerator in use requires about 3.5 kWh/liter of volume, as compared to 1.3 kWh/liter for the best model on the market in 1983 and as little as 0.5 kWh/liter for a laboratory prototype (Goldemberg, 1987). Utilization efficiency is difficult to estimate, but surely not very high. Japanese and European models tend to be smaller than US models, for instance. Many foods are cooled only for aesthetic reasons or out of habit. The need for refrigeration to preserve food is unlikely to be eliminated completely, but, in principle, it can be reduced sharply by increased use of new technologies such as sterile packaging.

## 2.3. Cooking and hot water

These items account for 2.5% and 3.2%, respectively, of total energy consumption. The APS Summer Study made an estimate of the average efficiency of *water heating* (3%) (Ross *et al.*, 1975). This refers to the thermodynamic efficiency of converting fuel and cold water into warm water delivered at the spigot. New gas-fired water heaters have improved somewhat in recent years (as noted above), but electric water heaters (except heat pumps) have not. The overall average efficiency of water-heating may have risen fractionally since 1972. Yet, it has been shown that overall efficiency of water heating could be increased by a factor of 3 (that is, losses cut by two-thirds) by relatively simple "fix-ups" of conventional heaters and pipes (Lovins, 1986).

Hot water use is inefficient in most laundromats and dishwashers due to repeated rinses with hot water. This appears to be attributable to a popular prejudice that hotter water *cleans better*. In fact, recent model washing machines have cut back sharply on hot rinsing. There is probably no physical reason to use hot water at all for dishwashing and laundry purposes, given the availability of effective cold water detergents. Demineralization of washing water would greatly increase the effectiveness of most detergents, thus compensating for the dubious benefits of heating. Lavish use of hot water for personal baths and showers can also be sharply reduced by means of *water conserving* flexible shower nozzles, without loss of amenity. These are already standard in Europe. Again, making use of solar heat or waste heat from refrigerators or cooking for heating water, together with reduced consumption, would make it possible to virtually eliminate all use of fossil fuels or centrally generated electricity for this purpose, except in extremely cold climates or bad weather.

It is difficult to estimate the overall efficiency of hot water use (as opposed to heating and distribution) either in 1972 or at present, due to lack of data. Assuming cold water detergents could suffice for all purposes except personal hygiene, use could probably be reduced by at least 75%. More efficient shower nozzles would save something like half of the remainder. This logic suggests a use-efficiency in the neighborhood of 10–15%, or an overall efficiency of hot water production and use between 0.3% and 0.4%.

Conventional cooking done over open gas burners or electric ranges uses heat very inefficiently, even by the low standards of other uses of energy. About half of the heat generated is lost directly as combustion products, or by radiation or connection. Most of the remainder heats metal pots and pans, which later reradiate the heat to the room. (Kitchens do get hot!) Direct-heat cooking in 1972 was probably barely more efficient than water heating (around 3%).

Since then, some improvements have occurred, however. Halogen-lamp IR cookers and insulated cooking pots have been introduced. Each saves about 10%. Magnetic induction electric stoves save about 40%, as compared to the older electric range designs. Microwave ovens, which heat only the food, are the most important advance. A typical full-size microwave oven currently draws 700 watts at full power, as compared with about 2.5 kilowatts for an 8 inch electric ring, or electric oven. Moreover, it is likely to cook the food in half or a third of the time required by conventional methods. The efficiency gain appears to be in the range of 7–10. This is roughly consistent with a 60–90% conversion of electric energy into heat energy *in the food* (given that the conversion efficiency for electricity itself is currently about 33% of the energy input). About half of all US households now own microwave ovens, although a much smaller fraction of all cooking is done in them, due partly to lack of user experience with timing. As food companies offer more *microwave-ready* packaged foods, the conventional electric or gas range may begin to phase out, except for cooks who truly like to cook fresh food from "scratch".

Apart from the above, many consumers tend to "overcook" in a technical sense, out of simple ignorance or habit. Dieticians frequently warn against this tendency, since it also destroys vitamins and flavor. It is noteworthy, in this context, that Germans and Japanese use only about one-third as much energy (gas) each year for cooking purposes as Americans, while even the *cuisine* oriented French use barely two-thirds as much (Goldemberg, 1987).

### 2.4. Lighting

Lighting consumes about 4% of US energy. Over half is used in commercial buildings. There are three types of electric lighting, *viz.* incandescent, fluorescent, and high intensity discharge. Incandescent lights currently average 16 Lumens/Watt (L/W), for fluorescent lights the average is 66 L/W, and for high-intensity discharge it is 48 L/W. The average over all types is 44 L/W.[12] The theoretical limit for white light (if all the electricity input were converted to visible light) is 220 L/W, so the three types of lighting devices are respectively 7.3%, 30%, and 22% efficient in terms of energy conversion. The overall average is 20%. (These figures must be reduced, of course, by the conversion efficiency of heat into electricity, which is about 34% on average.) Thus the overall efficiency of electric light production in the USA is currently about 7%.

As in all the other examples above, the *delivery* of the light is only part of the story. The efficiency with which the light is used must also be considered. Energy is wasted if light is wasted heating the fixture unnecessarily, or if more light is delivered than is needed. It is wasteful to use a bright light far away, when a less bright, but closer light is sufficient. It makes no sense to light an empty room. Moreover, light produces heat, and in hot weather, at least, electric lighting creates a significant additional load on ventilation and air-conditioning systems. In fact, this indirect load is estimated to be equivalent to about 25% of the primary electricity consumption for lighting purposes, or 1% of the national energy consumption.

How much energy could be saved by redesigning lighting systems to provide light where it is needed, without wasting it? On the basis of a detailed study by Lovins and Sardinsky (1988), the potential for energy saving with no loss of utility to the user, using commercially available equipment (such as compact fluorescent light bulbs) is estimated to be 92% of current electricity consumption. Moreover, the capital cost would actually be less than the present investment, resulting in net capital *savings* of 1.4 cents per kilowatt-hour (electric) saved (Lovins and Sardinsky, 1988). These savings are about equally divided between improved equipment and more efficient utilization. If we assume that light utilization were 50% efficient, on average, *after* the improvements recommended by Lovins et al, one would certainly have to conclude that current utilization efficiency is now below 10%. By this logic, the overall energy efficiency for lighting must be less than 0.7%.

## 2.5. Transportation

Automobiles and motorcycles account for about 12.3% of national energy consumption. Trucks, buses, railways, barges, aircraft pipelines, and military account for about the same amount. All except for a small fraction of railway mileage are propelled by internal combustion engines (gasoline, diesel or turbine).

Modern internal combustion engines operating under optimal speed and load conditions can achieve 33%-36% efficiency. (Diesels are at the upper end; gasoline engines at the lower end.) However, in practice, cars or trucks in traffic operate at less than half of their full load. This brings the efficiency down by a factor of one-third in typical stop-start traffic (i.e., the so-called *federal driving cycle*). Frictional losses in the drive train, especially the transmission, bring the net efficiency down by another quarter (to about 19%). Further, power delivered to the crankshaft must be used to run a number of parasitic loads including the electric generator, oil pump, water pump, fan, and air-conditioning. Collectively, these consume quite a lot of power and bring the net efficiency for cars down to 11%. If the transmission is automatic, there is a further drop to 8%. The majority of US cars are automatics, so an overall figure of 9% was estimated by the APS Summer Study cited above for 1970.

The foregoing analysis does not take into account energy consumed by oil refineries and evaporative losses in the fuel distribution system, which amount to something like 10% of the energy content of the crude oil. Taking this into account an average of 8% energy efficiency can be assumed for US automobiles and local delivery vehicles (pickups and vans) for 1970.

Moving the car is not an end in itself. The vehicle moves to provide transportation for passengers and/or freight. The relevant measure of service provided is passenger-miles traveled, or freight ton-miles carried. But most vehicles are not fully occupied, and even if they were, most of the weight transported is that of the vehicle, not its contents. Average automobile occupancy in 1969 was 1.9 persons per car, for all uses, although the average car could carry between 4 and 5 passengers. The average car in 1970 weighed close to 3500 lbs, although its *payload*, even when fully loaded, was closer to 300 lbs. In effect, the *payload efficiency* of automobiles in 1970 was 8% to 9%. Combining vehicle payload efficiency with vehicle energy efficiency gives an overall service efficiency in the range of 0.6-0.7% for cars in 1970.

Since the early 1970s there have been useful savings in several areas. The average fuel-economy of all US cars was about 14 miles per gallon (mpg) in 1972. It is around 20 mpg today for the fleet average and 28 mpg for 1988 models. How can one account for the recorded improvement? A number of factors contributed. Radial tires *flex* much less than the bias-ply tires used in the 1960's, with measurable fuel savings. Better aerodynamic design has also resulted in reductions in air resistance. Transmission frictional losses have been cut significantly by several innovations, including 5-speed gearboxes. Microprocessor controls help the engine run closer to optimal speeds and help the transmission to change gears at the optimal points. On the other hand, engine compression ratio's are actually lower, as noted earlier.

Much of the improvement so far is undoubtedly due simply to removing excess weight from vehicles. Average vehicle weight for new cars is down about 1000 lbs since 1970 and over 600 lbs since 1976. An interesting sidelight is that, while cars are smaller, average occupancy has risen. In 1979 it was about 2.5 passengers. (Allowing for reduced vehicle weight, it appears that payload efficiency is now more like 450/2500 = 18%). Overall system efficiency has risen to around 2%. Nevertheless, there is still plenty of room for improvement: at 50 mpg for vehicles, the overall energy efficiency of automobile transport would still be less than 4%.

Several foreign manufacturers now produce cars capable of getting better than 50 mpg for average driving. The Toyota AXV (prototype), introduced in 1985 exhibited a fuel economy of 98 mpg on the Environmental Protection Agency's (EPA) federal driving cycle. It weighs 1430 lbs and has a direct-injection diesel engine. At least seven foreign car makers have introduced prototypes capable of 67 to 121 mpg (Goldemberg, 1987 and Bleviss, 1988). This is possible because of interdependence: fuel consumption is proportional to engine power, most of which is needed to move the car, while a significant part of the weight of the car is devoted to structures to support its own weight. Thus, it appears possible to go on reducing both vehicle weight (by introducing lighter materials) and engine power in tandem, without sacrificing actual performance, for many years to come. A fleet average of 100 mpg would constitute a 7-fold improvement of as compared with the US fleet average for 1970, and 5-fold as compared with 1986. Yet the overall energy efficiency of personal transportation might still be no higher than 7%!

Trucks and buses can achieve somewhat higher overall efficiencies to the extent they attain higher payloads. Buses and trains in Europe use only a quarter to a fifth the energy per passenger mile that private cars do. In crowded Japan public transport facilities are even more intensively used. The major problem in the USA is low utilization, especially during off-peak hours. Increasing energy efficiency is tantamount to finding ways to increase seat occupancy. However, in the USA long-distance diesel tractor-trailers consistently do achieve payload efficiencies (carrying freight) in the 50% range resulting in overall energy-conversion efficiencies of 12-15%. Freight-carrying railroad trains are more efficient still, probably approaching 25%.

Airliners and air-freight carriers, operating at 75% of nominal capacity, actually achieve only 25% payload capacity. (Roughly one-third of the total fully-loaded weight is the airframe and engines, and one-third is the fuel.) Assuming nominal engine efficiency to be 40%, but that 10% of the mileage flown is wasted due to weather and congestion problems, 20% of the fuel is used climbing to cruising altitude and 20% miscellaneous parasitic losses, the overall efficiency of aircraft transportation would appear to be about $0.25 \times 0.225 = 5.5\%$. This is, nevertheless, considerably better than private autos, if not quite as good as buses or trains can be.

It must be emphasized again that, although the above estimates are necessarily imprecise, there can be little doubt that automobile transportation remains extremely inefficient. Thus, there is still enormous scope for further savings.

## 2.6. Industry

Industry, including agriculture, mining, manufacturing, and construction, is the biggest energy consumer among the three major sectors of the US economy (40% of the total). Within this sector, 50% of the energy is consumed as fuel for process heat, 17% is non-fuel uses, 12% is used as fuel for internal combustion engines and the remainder (21%) is electricity (gross), for electric furnaces, electrolytic processes and electric motor drive. Industrial use of energy in 1979 is broken down further in Appendix A.

The industrial sector is also, arguably, the most efficient energy user. It is easier to be efficient when operating on a large scale. Moreover energy is an explicit element of operating cost. Managers are forced by competition to analyze costs carefully. In industries (such as petrochemicals) where energy costs are a significant fraction of total costs, managers are more alert to opportunities for savings. In industry it is rare for *best practice* technology to be more than 20% or so better than average. (Among private households the range is at least one order of magnitude greater.)

In contrast with the transport and building sectors which produce services, the outputs of industry are material in nature. Thus, there is a minimum theoretical need for (free) energy per mass unit of each product, be it ammonia or stainless steel. On the other hand, there is no lower limit to the quantity of material products required to sustain life (except for food), or to generate a dollar of GNP. Even if there were such a minimum, there is no fundamental reason why most finished materials, once separated from their raw forms, could not be recycled and reused many many times. (True, the second law of thermodynamics implies that recycling can never be 100% efficient, but it is also true that there is no absolute ceiling on efficiency below 100%.)

Feedstocks account for about 5% of industrial energy. About a third of the energy content of chemical feedstocks is embodied in "final" chemicals, such as plastics. About 25% of the energy consumed in the steel industry is embodied in iron and steel, while 15% of the energy used in aluminum production is embodied in aluminum itself. The remaining direct consumption of fossil fuels (and some electricity) provided process heat for chemical, mineral, and metallurgical processes. At present, most process heat is delivered in the form of steam. An efficiency of 25% is usually assumed, see for example, Ross *et al.* (1975) and OTA Report (1983). Olivier *et al.* (1983) have estimated an average efficiency of 14% for process steam in the UK. I suspect the latter figure is more realistic.[13]

The biggest users of process heat are the steel, petroleum, chemicals, and pulp and paper industries. A comparison of actual energy use in these industries in 1968 with theoretical minima has been carried out by Gyftopoulos *et al.* (1974) and Holl *et al.* (1975). The results are expressed here in terms of percentage efficiency: iron and steel manufacturing 22.6%, petroleum refining 9.1%, primary aluminum 13.3%, cement production 10.1%.

The pulp and paper industry currently uses as much as three-quarters of a ton of oil per ton of paper produced. However, in principle, the industry should be able to supply essentially all its own energy from lignin wastes. It should not need any purchased fuel. Since the theoretical minimum may be negative a meaningful percentage efficiency cannot be computed.

Rising energy prices have induced significant savings in all these industries. Energy input per unit manufacturing output (based on the FRB Index of industrial production) declined from 100 in 1970 to 63.4 in 1984 (Doblin, 1987). Of this decline, about half was due to structural change and about half of the remainder to changes in output mix. Focussing on purchased energy for heat and power, the contribution of technological change was about 33%. In effect, one may conclude that energy consumption per unit of *physical* output declined by about 12% during the 1970-84 period.

In 1983 the Office of Technology Assessment projected declines of 39% in the unit energy requirements for steel, 10% for petroleum refining (despite some increased energy requirements due to the elimination of tetraethyl lead), 9% for the chemical industry, and 25% for paper-making, from 1980 to 2000 (OTA, 1983).

These expected improvements do not nearly exhaust the potential savings. They also assume no increase in the efficiency of electricity generation (33%) or process-steam generation (25%). A great deal of process heat is still used simply to remove water where it is not wanted e.g., from brines, alkalis, etc. In principle, this could be done by using solar energy (Kreith and Meyer, 1983) or waste heat from higher temperature processes such as coking, iron-smelting, and steelmaking. The problem is a practical one of efficient heat transfer from locations where heat is available to locations where it is needed. One approach, increasing in popularity, is for firms to generate their own electricity on-site, using the low temperature waste heat for process purposes (Gyftopoulos *et al.*, 1974 and Diamant, 1970). Another source of very large potential savings would be to utilize combustible process wastes, especially carbon-monoxide, for fuel (Rohrmann *et al.*, 1977).

The chemical industry is difficult to analyze because its inputs are not clearly segregated between fuel and feedstock. A detailed energy analysis for about 80 major chemical processes was carried out by Ayres *et al.* (1983). In this analysis no attempt was made to calculate thermodynamic minima for each process, but ratios of the available energy in the product to the available energy of all inputs were computed. (Thus high-energy products like acetylene tend to have high ratios.) Typical *best available technology* output/input ratios are given in *Table 1*, with losses as a fraction of total inputs in the second column.

*Table 1.* Best available technology output/input ratios for various chemical products in 1980.

| *Chemical product* | *Output/input ratios* | *Losses as a fraction of total input* |
|---|---|---|
| Acetaldehyde | 0.73 | 0.27 |
| Acetic acid | 0.62 | 0.38 |
| Acetylene | 0.75 | 0.25 |
| Ammonia | 0.61 | 0.39 |
| Butadiene | 0.75 | 0.25 |
| Chlorine/caustic soda | 0.63 | 0.37 |
| Chloromethanes ($CHCl_3$) | 0.50 | 0.50 |
| Cumene | 0.82 | 0.18 |
| Ethanol | 0.70 | 0.30 |
| Ethylene | 0.85 | 0.15 |
| Ethylene glycol | 0.67 | 0.33 |
| Ethylene oxide | 0.62 | 0.38 |
| Formaldehyde | 0.72 | 0.28 |
| Methanol | 0.69 | 0.31 |
| Polyethylene | 0.88 | 0.12 |
| Phosphoric acid | 0.65 | 0.35 |
| Sulfuric acid | 0.28 | 0.72 |

Of course most chemical products are intermediates used in the production of other chemicals. Thus final products are made by *chains*, or sequences, of processes with an overall conversion ratio which is the product of the conversion ratios at each stage.[14] If the typical chain has three steps, each of which has a conversion ratio of 0.7, the overall conversion ratio of the chain is around 0.34. A 4-step chain would have a ratio of around 0.25. That is, the available energy of the final product might be somewhere between 25% and 34% of the available energy of the original feedstocks. (A third was used above.)

The energy conversion efficiency (in terms of theoretical minimum energy use divided by actual use) cannot be computed directly from these numbers. However, it is unlikely that the thermodynamic efficiency of chemical processes in general is as high as the efficiency of petroleum refining, which was about 9% in 1968 (Gyftopoulos, 1974) and may be 12–14% today, simply because large petroleum refineries are able to take advantage of scale economies and co-production savings (economies of scope) not feasible for smaller operations.

The efficiency of a sequence of processes is the ratio of the minimum theoretical conversion loss to the actual losses. This is the product of the efficiencies of the individual steps in it. Assuming 3 steps and 10% at each step, the industry as a whole is presumably operating now at something like 0.3% feedstock efficiency and 0.1% energy efficiency. (The latter figure may be off by a considerable factor either way.) Clearly, a powerful long-term strategy for improving overall efficiency in the chemical industry is the development of new processes to shorten these chains, bypassing as many intermediates as possible. Ideally, one would like to be able to produce final products like polyethylene or synthetic rubber directly (i.e., in a single step) from feedstocks such as ethane or propane, or even from crude oil. Bio-technology offers exactly such a prospect of radically higher efficiencies.

The last major category of industrial energy use is *electric drive* of machine tools and other equipment. This accounts for roughly three quarters of electricity purchases by industry. (In fact, half of *all* electricity is used to drive motors.) Electric motors are generally regarded as very efficient, with *nominal* efficiencies of 90%. Yet in the aggregate, losses are considerable and large gains are still possible. (A number of motor control improvements, especially variable frequency drives for induction motors, could cut aggregate consumption by a factor of two, at least.)

However, the greatest opportunities for improvement lie in the realm of motor-utilization. Metal-cutting is among the biggest uses. The efficiency of the metal-cutting process has increased spectacularly, even since 1960, due to the introduction of harder cutting materials (e.g., alumina-coated carbides). It is not known what the theoretical limits might be for cutting by means of conventional hard-edged cutting tools, but technical progress in this field continues unabated. Harder tools permit much higher cutting speeds with no greater power consumption. Assuming motor and drive-train losses can be cut be at least a factor of two, and that cutting speeds can be increased by at least a factor of 30 without running into any physical limits [15], one would have to assume that the efficiency of electrical energy use for metal-cutting is no better than 1.5%. As a matter of fact, the ultimate lower limit of energy requirements for metal-cutting is probably quite close to zero, by current standards. For other applications of motors I would expect similar results.

I hesitate to estimate the overall efficiency of the US industrial sector. The APS Summer Study did not attempt it, except to note that there is, on average, a 75% loss in generating process steam, probably an understatement, and a 65% loss in generating electricity. Except for non- fuel uses and carbothermic reduction processes (e.g., steel), these two account for most energy use in industry. In summary, it appears that feedstocks are currently used with an efficiency of 30-35%, iron & steel operates at about 25%, primary aluminum around 15%, petroleum refining is probably now somewhere around 12%, cement is a bit less, while paper and chemicals are much lower. However, precisely because of their energy-intensity, the incentives to conserve have been greatest in these industries. Elsewhere, where little energy is embodied in the product itself and energy costs have been comparatively insignificant as a fraction of total costs, energy efficiencies tend to be extremely low (as in the R&C sector). However, taking into account energy embodied in industrial products, an overall efficiency in the neighborhood of 10% for industry appears reasonable.

But once again, production per se is not the whole story. Bearing in mind that steel, aluminum, paper, and plastic all embody significant amounts of energy, the question is: how efficiently are "final" materials subsequently used?

Do we need to process as much material as we do? Metals that are recycled require much less energy to rerefine than do virgin metals. The same is true of textiles, paper, and even lubricating oils. In principle, the energy embodied in metals, paper and plastics is not really lost until the metals themselves are dispersed in chemical form or corroded beyond recoverability. If energy-containing materials were not dispersed and lost, we would not need to produce replacements.

The percentage of a metal that is recycled depends on its economic value. It is very high (around 70%) for gold, comparatively high for silver, copper, and lead, somewhat lower for iron and steel, aluminum, zinc, and paper. Roughly 35% of the embodied energy in metals (taken in the aggregate) is currently saved by recycling. This figure is up considerably since 1970, though far less than it could be (Chandler, 1983). On the other hand, the recycling rate for paper was only 26% in 1980, and the rate for plastics is currently no more than 1%. To develop a more conservative technology for utilizing (and recycling) lubricants, solvents, plastics, and synthetic fibers is a major challenge for the future. In any case, combining production efficiency (10%) with recycling efficiency (surely less than 25% for the average of all final materials, and negligible for plastics), yields an overall energy-use efficiency in the range of 2.5% for industry overall.

## 3. The Bottom Line

A brief summary is in order. Very roughly, the *building* sector (residential and commercial) in 1979 accounted for 32% of total US energy consumption, industry accounted for 40%, and transportation accounts for 25%. (The other 3% was unaccounted for.) These relationships vary slightly from year to year, of course, and the industrial share is generally declining. Taking the R&C category first, the overall efficiency of providing the services of space heating and cooling, water heating and cooking, (which jointly account for about 80% of the total) appears to be less than 0.4%. The remainder of the energy consumed in this sector is mostly for illumination. A reasonable estimate for the overall efficiency of electric lighting is 0.7%. Assuming the unaccounted for uses are not dramatically more efficient than the ones accounted for, a reasonable estimate for the R&C sector as a whole, then, would be 0.6%.

Allowing a conservative 2% for automotive travel, and 7% for non-automotive transportation services (primarily freight), and taking the estimate of 2.5% for industry as a whole, the average energy-use efficiency of the US economy (*ca.* 1988) comes out to be 2.5%.

### 3.1. Is 2.5% efficiency too low?

It is not immediately obvious whether a 2.5% efficiency of energy use is anything to worry about. A "hard-line" free-market economist might well be inclined to argue that the current figure *must* be optimum, given current energy prices and costs of introducing energy conserving technology. Some sophisticated analysts go on to point out that there are tradeoffs between thermodynamic efficiency and other societal objectives, including the cost of capital and the cost of time (Weinberg, 1977). It is pointed out (with some justice), for instance, that engine designs which maximize power output do not maximize energy efficiency. Similarly, speed is valued because it saves time, but is achieved at the cost of greater energy consumption. (In fact, for aircraft, power consumption increases roughly as the cube of speed. For ships there is a similar relationship.) Because I agree that society values time (among other things) I have explicitly assumed that society will continue to demand the same mix of final services (including private autos and air transportation) that it does now.

The suggestion that the present choice of technologies to meet the demand for final services is optimum presupposes the existence of a perfectly competitive free market for energy, materials, and environmental amenities. Several key conditions for such a market are clearly not met in the case of energy. One is the absence of externalities or "third party" effects. Another is the availability of perfect information about all supply and demand schedules to each actor. Economic rationality dictates that energy prices should be set (either by the market itself, or by the government if the market is not functioning), to cover marginal costs of production *plus* an allowance to cover unpaid social or environmental costs of fossil fuel combustion. These costs range from acid mine drainage and black lung disease to acid rain, smog, and the greenhouse effect. Unfortunately, most of the social and environmental costs associated with energy use are being left to our children and grandchildren to pay in the future.

How big are the unpaid social and environmental costs? One recent article estimated damages due to thermal power station use per ton of coal equivalent (TCOE) as follows: Coal US$107–117, residual oil US$92–106, gas US$30–36 (Chizhov and Styrikovich, 1988). Costs associated with other uses of fossil fuels are likely to be larger, since emissions from industrial boilers and small heating plants are far less well controlled than emissions from electric power generating stations. In other words, unpaid costs that can be accounted for (damages) are of the order of 2.5 times the actual (paid) cost of coal, US$45/metric tonne, and are only slightly less for oil. Even the most benign fuel, natural gas, generates unpaid damages comparable to the paid cost of the fuel itself.

While these numbers are very uncertain, there is no uncertainty about the fact that they are large compared to the *paid* costs of extraction, conversion and distribution. Indeed, the compilation cited does not even consider all of the known adverse effects, since some of them are literally incalculable (Chizhov and Styrikovich, 1988). The true numbers are more likely to be higher than lower. In summary, the *true* shadow-price of fossil energy consumption is probably at least 3–4 times the current market price of energy. In effect, current energy consumption is being quite heavily subsidized at the expense of human health and both local and global environment.

Notwithstanding these facts, many countries (including the USA) subsidize energy prices – for the benefit of some consumers, at least – at a level even below marginal cost of production and taking no account at all of the unpaid environmental costs. In the USA identifiable subsidies of various kinds amounted to over US$48 billion in Fiscal Year (FY) 1984, of which 65% was for electric utilities and the nuclear industry according to one count.[16] In addition, it is clear that a substantial chunk of the US Defense Department budget can be allocated to the costs of *projecting* US military power overseas. One standard justification is to preserve access to the oil reserves in the middle-East. [The Pentagon will not be anxious for the full costs of the Persian Gulf operation to be publicized, but US$14.6 billion for the last year, or US$52.61 per barrel has been reported (Daschle, 1988).] These costs for security of supply are paid by US tax-payers, not by US energy consumers (and still less by the consumers of Europe and Japan who purchase most of the middle-eastern oil). In a rational world, these costs would be paid by the consumers through a tax on their oil imports.

Another kind of market failure results from imperfect availability of information, especially to consumers. In a perfect market the buyer of a house should take into account the capitalized value of the lifetime costs of operating that house. A house with efficient heating/cooling equipment and good thermal insulation will cost very little to operate, leaving the buyer with considerably more cash available each month to pay principal and interest. Unfortunately, it doesn't work like that. Buyers know too little to ask sellers the right questions, and mortgage lenders ignore operating costs in their calculations of how big a mortgage a buyer can afford. The US government has made no effort to fill this information gap. Consequently builders have almost no economic incentive to install energy-conserving equipment, even if it would pay for itself in a few months. (In fact, as was noted in [7], less than US$3,000 added to the price of a typical Arkansas house would result in annual savings of the order of US$1900 in electricity and gas costs alone – enough to pay the additional cost in less than two years.)

The same thing is true, for the same reason, of landlords and tenants. In practice, tenants do not know enough (or are unwilling, for various reasons) to insist upon energy efficient lighting systems, heating/cooling equipment, and cooking stoves. This allows (actually, induces) the landlord to install the cheapest possible equipment – which tends to mean the least efficient.

The shift away from fossil fuels toward renewable sources of energy, and greater use- efficiency, will necessarily occur sooner or later no matter what actions the government takes. But, for the reasons noted above, sooner is a lot better than later. The pace of change, if not its ultimate direction, is within the province of policy. I shall now turn to some specifics. (For a much more comprehensive list, see Chandler *et al.*, 1988).

## 4. Some Policy Implications

National defense apart, there are three kinds of federal intervention that can be justified in our free market economic system. The first is to create and maintain a stable framework with which the private sector can function effectively. Tax policy, monetary policy, fiscal policy and trade policy fall into this category. With regard to energy conservation, however, the net effect of US tax policy has been to minimize consumption taxes in general, and to reject taxes on energy use in particular. On the other hand, as noted above, there are both direct and indirect (tax) subsidies for most forms of energy production, especially nuclear electric power. The small federal gasoline tax, unlike other excise taxes, is specifically reserved for financing highway construction and repairs.

As compared with other countries, at least, the United States effectively encourages both energy production and private automobile ownership and use. Indirectly, the trucking industry has been subsidized at the expense of the railroads. The subsidies to private homes (including mortgage interest deductions) further encourage private automobile use. Whatever the merit of such policies when the USA was the world's biggest oil producer and exporter, it no longer makes the slightest sense to encourage, still less subsidize, either energy use in general or inefficient forms of transportation. If the transport sector had to purchase energy at its *full* cost, including allowances for replacement of depleted sources and environmental damages, it is likely that buses and trains would be far more intensively utilized, as they are in Europe and Japan.

The second kind of justifiable federal intervention is to compensate for market failures or externalities. Both environmental regulation and the need for government subsidies to basic research are examples of government intervention to achieve public goods that the private sector would not undertake without specific incentives to do so. Both regulation and taxation are ways of structuring incentives to change behavior.

Consumerists often argue against taxing gasoline or crude oil as a revenue measure on the grounds that such a tax would be regressive, hurting farmers and low income people most. Industry opposes anything that might increase costs, and industry lobbyists argue that to do so would make US producers less competitive. Some argue that to tax imports only would be a bonanza for domestic producers and would merely induce them to use up remaining domestic reserves faster. I think the first of these points has some merit, but it is not decisive at a time when unemployment is so low. What better time to cut aggregate demand? The competitiveness argument is not well taken, since manufacturers in other industrial countries pay more for energy than ours do, but have managed to achieve lower costs in most sectors. Low energy prices in the USA amount to a subsidy, which is another form of protectionism. In the past it has tended to discourage investments that would increase efficiency in the use of energy and other resources.

In principle, there are two great benefits of using taxes rather than regulations to induce behavioral change. In the first place, taxes are theoretically more efficient than regulation as an instrument of change. Their impact is more penetrating and broader. Those affected are far less likely to hire lawyers and fight it out in the courts. In the second place, taxes create revenue. At the present time, the federal government needs revenue very badly. I need not comment further on this rather obvious point, except to say that an energy tax, or even a carbon-tax and/or a sulfur tax, would begin to redress the balance.

Yet, despite the theoretical advantages of taxes over regulation, there are instances where regulation achieves more at less cost. The Corporate Average Fuel Economy (CAFE) standards for automobiles seem to be a case in point. If revenue is not an issue, at least, it can be argued that fuel economy standards applied to the auto manufacturers (of which there are only a few) achieved more energy savings, at less cost to consumers, than any other government policy initiative of the past twenty years. From 1977 through 1985 CAFE standards mandated an increase in automotive fuel economy that halved oil imports and saved consumers a cumulative US$260 billion in fuel (1987 US$) at a cost of perhaps US$80 billion (Lovins, 1988c). It is very unfortunate that lobbying from Detroit has persuaded the Reagan administration to weaken the standards. In view of the success that has been achieved with automobiles it would seem more sensible to extend the idea to cover major home appliances, air-conditioning, and heating systems.

The net impact of a *hands off*, consumer-oriented approach to both energy and environment is to continue the *status quo*. However, the *status quo* is no longer a safe or sensible objective. Both environmental considerations and national security considerations strongly suggest major efforts to reduce our dependence on hydrocarbons in general, and imported oil in particular. But with an oil glut keeping prices down, the private sector has little or no incentive to invest in alternative technologies. With a longer time horizon and no need to maximize short-term profits for stockholders, the federal government is the only possible research sponsor of long-range, high-risk energy conservation (and environmental amelioration) projects. Unfortunately, the federal government has sharply reduced its commitments in this area in recent years.

The third type of intervention by the federal government is to provide leadership or public information and education. It is entirely appropriate, and indeed necessary, for the federal government to take the responsibility to provide important kinds of information to the public, if only to compensate for the market failures already noted. This is as true for energy conservation as it is for AIDS or drug abuse. Indeed, many serious policy analysts would put this governmental function first in importance.

The introduction of energy-efficient housing technologies has been much slower than it could be, because most architects and builders are still unfamiliar with energy-conserving technologies and the uninformed public does not demand them. It must be pointed out, too, that vested interests in the conventional heating technologies – including both manufacturers of heating systems and suppliers of fuels – have resisted real efficiency improvements (such as *super windows*) and touted *energy conserving* new furnaces instead. Unfortunately, once built, an inefficient building may go on wasting energy for many decades.

One major difficulty that must be faced is that builders currently have very little incentive to utilize energy-conserving technologies, especially if they add to the initial price of a house. There may be other approaches, but one possibility is federal legislation to give utilities, both gas and electric, the right to impose *hook-up* charges in proportion to the estimated future consumption of each type of energy, based on the characteristics of the heating systems and kitchen appliances built into the house.

A critical (and relatively inexpensive) function of the federal government, here, is to speed up the flow of information about *existing* technologies for energy conservation, especially in housing construction. A related governmental function is to recognize and compensate for the *payback gap*, which differentiates private individuals from profit-making enterprises. For the latter, an investment is justified if it pays for itself within a period corresponding to a financial return (after taxes) a few points higher than the current cost of capital. Payback periods of five to eight years are considered reasonable. On the other hand, it is a fact of life that ordinary consumers seem to be reluctant to make capital improvements on their homes unless the payback is extremely short – typically one year or less.

It is not suggested that the federal government can, or should, attempt to exhort people to behave differently. However other, subtler, mechanisms do exist. One plausible mechanism would be to give electric and gas utilities the statutory right to impose ***hookup*** charges in proportion to estimated future energy consumption, based on the thermal characteristics of the house and the efficiency of its heating/cooling systems. Another possibility would be to force banks to take estimated energy costs into account explicitly in determining the maximum monthly payment, and thus the maximum mortgage, that the prospective homeowner can afford.

To summarize, in view of the gross inefficiency with which energy is now utilized in the USA (indeed, the world), and in view of the extent to which market failures have contributed to the situation, a far more aggressive government policy of encouraging energy use efficiency is justified and overdue, on national security grounds alone. There is no need and no excuse, for the USA to be dependent on imported petroleum. The benefits of increased energy use efficiency to the dismal US balance of trade are obvious. Imported oil accounts for over US$40 billion of our annual import bill, which could rise to US$200 billion by the end of the century. Yet it is neither necessary nor wise to respond, as some have argued, by embarking on a new and ambitious program of synfuels or nuclear power development (Abelson, 1987). Increased efficiency of use is a far more cost-effective alternative. In the longer run, it is only by sharply increasing the efficiency with which energy, especially carbon-based fuels, is used *worldwide* that the developing countries can grow economically without posing an intolerable threat to the world's climate via the greenhouse effect (WCED, 1987).

## Notes

[1] Thermodynamic theory is gradually recognizing this reality, and a new subfield, *thermodynamics of finite time* is emerging. For example the notion of thermodynamic availability has been extended to *finite time availability*, and wholly new tools for thermodynamic analysis are being developed. See, for example, Andresen et al. (1984).

[2] A study carried out a dozen years ago by the author and a colleague using 1971 data arrived at a slightly lower estimate, viz. 1.6% (Ayres and Narkus-Kramer, 1976). It used a similar methodology, though differing in some details from the present analysis. Not surprisingly, there have been some improvements since 1971.

[3] In 1973 a pamphlet entitled *Understanding the National Energy Dilemma* was prepared by the staff of the Joint Committee on Atomic Energy (JCAE) of the US Congress (Bridges, 1973). The schematic presentation employed in that pamphlet (shown in *Figure 1*), together with its hidden underlying assumptions, has been

adopted as a standard, not only in the US government, but by the key international agencies concerned with energy policy (ECE, 1976). In this tradition, efficiency is defined as the ratio of "useful energy" to the total of "useful" and "rejected" energy. For instance, this typology is built into the official *energy balances* that are published annually by most OECD countries and which have been compiled since the mid 70's by the International Energy Agency (IEA).

[4] Quote from Singer (1988). Other examples of *conventional* forecasts include [CONAES (1979), Schurr *et al.* (1979), Ridker and Watson (1980), and Häfele (1981)]. In fairness, it must be pointed out that others have argued for a much greater role for conservation. Amory Lovins, who coined the phrase *soft energy paths* in the title of his book and articles, has been one of the most influential, albeit controversial (Lovins, 1977 and 1978). A recent study sponsored by the World Resources Institute has reached many of the same conclusions from a slightly different direction (Goldemberg *et al.* (1987).

[5] In fact, elimination of tetra ethyl lead from gasoline has resulted in an actual *reduction* of the maximum thermal efficiency of automobile engines from about 36% to 33% – other factors remaining equal – due to the reduced compression ratios of present-day engines. This is an efficiency loss of nearly 10%. Yet the average automobile fuel economy of new cars, measured in vehicle-miles per gallon, has actually doubled since 1970.

[6] The delivery efficiency of an electric heat pump can be expressed as a product of the efficiency of electric power generation (about 33%), times the coefficient of performance (COP), times the factor $\{1-T_c/T_w\}$, where $T_c$ is the temperature of the cold reservoir (usually the outside air) and $T_w$ is the temperature of the warm reservoir (the inside of the house). Current heat pumps have an average coefficient of performance (COP) of about 1.7, but high performance systems are now available with COP's close to 3. Thus, the overall efficiency of such a system is proportional to the temperature difference between the interior and the cold reservoir. If the difference is of the order of 30°C, the overall efficiency of an electric heat pump would be of the order of 10%. For more details see Williams *et al.* (1983).

[7] See also Williams *et al.* (1983). In this context it is also worth mentioning the results of a *model* analysis carried out recently for the State of Arkansas (Lovins, 1988a). The study was concerned primarily with the potential for reduced electricity consumption, from all uses (including, but not limited to, heating and cooling) but it pointed out that many of the measures that would save electricity would also save gas. For a "typical" (1400 square foot) centrally air-conditioned Arkansas house, with a mix of electric and gas heating, it was found that a modest retrofit costing US$988 (1986US$) would save US$895 *per year*, while a more comprehensive retrofit costing US$5053 would save US$1749 annually, in total energy costs. Not surprisingly, if the equivalent items were incorporated in new construction, the added cost would only amount to US$2712, while the annual savings would rise to US$1913. For the low cost retrofit the most effective items were (1) E,S,W window film (2) a more efficient but smaller air-conditioning unit, (3) double-glazing of windows. It appears that windows offer by far the greatest opportunity for improvement. Conventional double-glazed windows costing US$5-6 per square foot, found in many homes, have a thermal insulation "R-value" of only 1.9. Triple glazing increases the cost to US$8-9 and the R-value to 2.9. However, using special reflective coatings and inert gas fillers (e.g., argon) now commercially available, *super windows* with R-values as high as 12–13 can be obtained at an *added* cost of no more than US$2-3 per square foot.

[8] Ultrasonic-doppler room occupancy sensors are available from as many as 20 manufacturers. They cost US$30–80 each, installed. Obviously such sensors are

applicable only where space-heating/cooling is already controlled on a sectoral basis. This is one of the advantages often cited for electric heating systems.

[9] In the Canadian case, it has been estimated that net extra costs for an average (US$80,000) house would be US$3000 (ACEEE, 1984). For the Arkansas "model" case (see [7]), air-conditioning is more important than heating. If "super windows" were incorporated in new construction, the net cost would actually be negative, because both space heating and air-conditioning requirements would then drop to negligible levels with corresponding capital savings in central air-conditioning and ductwork (Lovins, 1988b).

[10] The average air-conditioning unit in service in the US today has a SEER value of 7. The average new unit has a rating of 8, while the average new central unit has a rating of 9. By comparison, the best unit produced in the US has a rating of 12, the best unit mass-produced in Japan has a rating of 15, while the best commercially available unit made in Japan has a rating of 16.

[11] One of the assumed *stage 1* retrofits in Lovins' Arkansas study was that a 6-ton air-conditioner with a SEER of 7.0 (national average) was replaced by a 2-ton unit with a SEER of 9.5. For the assumed "stage 2" retrofit, a 2-ton unit with a SEER of 15.5 was assumed (Lovins, 1988a).

[12] Data courtesy of A.B. Lovins. (See Lovins and Sardinsky, 1988 and Goldemberg *et al.*, 1987.)

[13] At a temperature of (200°C) only about 40% of the heat is thermodynamically available to do work. At 300°C the available fraction is less than 50%. Assuming furnace efficiency of 70% and distribution losses of 50% or so would account for a 14% overall efficiency.

[14] The *chain* analogy is an oversimplification, of course, because many processes yield more than one useful product (the chlor-alkali industry is an obvious example) while many products also require two or more inputs so the system as a whole is more like a network.

[15] The current state-of-the-art machine tools cut at around 3000 sfpm. The average for all machine tools on shop floors (most of which are fairly old) is probably between 500 and 1000 sfpm. (Accurate data is not available). However high speed prototype cutting machines have already achieved well beyond 30,000 sfpm with coated carbide tools. Given the recent development of technologies for diamond- coating, and their recent application to cutting tools, much higher speeds appear to be potentially achievable.

[16] More specifically, nuclear power received 34% of all federal subsidies, consisting of US$2.3 billion in direct line-item expenditures, US$10.2 billion in tax breaks and 3.3 billion in subsidized financing from government agencies. It produced only 5.5% of US energy in that year. Non-nuclear electric power accounted for over US$14 billion in various subsidies. Fossil fuels (primarily oil and gas) received most of the rest (Lovins and Heede, 1985).

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## Appendix A: US Energy and Electricity Consumption in 1979

| | *Total energy* | *Inputs to electric power* | *Inputs to motive power* | *Inputs to non-fuel uses* | *Inputs to direct heat* | *Electric power consumed* |
|---|---|---|---|---|---|---|
| GRAND TOTAL | 81.142 | 21.612 | 23.553 | 5.651 | 27.752 | 6.903 |
| Not accounted for | 2.574 | | | | | |
| Electric transmission loss | 2.070 | | | | | |
| Other not accounted for | 0.504 | | | | | |
| Total accounted for | 78.568 | 21.612 | 23.553 | 5.651 | 27.752 | 6.903 |
| Industry, total | 32.512 | 8.698 | 2.962 | 5.651 | 15.201 | 2.740 |
| Agriculture, fish, forestry | 1.352 | 0.329 | 0.796 | | 0.227 | 0.106 |
| Mining, total | 2.818 | 0.615 | 1.664 | | 0.539 | 0.165 |
| Oil and gas | 1.982 | 0.244 | 1.518 | | 0.220 | 0.046 |
| Other | 0.836 | 0.371 | 0.146 | | 0.319 | 0.119 |
| Manufacturing, total | 28.162 | 7.754 | 0.322 | 5.651 | 14.435 | 2.469 |
| Food and kindred | 1.233 | 0.442 | 0.047 | | 0.744 | 0.142 |
| Paper and allied | 2.543 | 0.642 | 0.020 | | 1.881 | 0.207 |
| Inorganic chemicals | 1.186 | 0.855 | 0.009 | | 0.322 | 0.255 |
| Organic chemicals | 1.606 | 0.404 | 0.014 | | 1.188 | 0.130 |
| Products of oil, coal | 3.529 | 0.393 | 0.015 | | 3.121 | 0.126 |
| Stone, clay and glass | 1.503 | 0.350 | 0.044 | | 1.109 | 0.113 |
| Primary metals | 5.673 | 1.994 | 0.045 | | 3.634 | 0.642 |
| Metalworking (33–37) | 2.227 | 1.250 | 0.052 | | 0.925 | 0.396 |
| Other manufacturing | 3.011 | 1.424 | 0.076 | | 1.511 | 0.458 |
| Non-fuel | 5.651 | | | 5.651 | | |
| Construction | 0.180 | | 0.180 | | | |
| Non-industry, total | 46.056 | 12.914 | 20.591 | | 12.551 | 4.163 |
| Transportation | 20.103 | 0.189 | 19.731 | | 0.183 | 0.061 |
| Freight | 8.038 | 0.160 | 7.873 | | 0.005 | 0.052 |
| Highway | 5.311 | | 5.311 | | | |
| Other | 2.727 | 0.160 | 2.562 | | 0.005 | 0.052 |
| Passenger | 12.065 | 0.029 | 11.858 | | 0.178 | 0.009 |
| Auto and cycle | 10.029 | | 10.029 | | | |
| Air, total | 1.705 | | 1.535 | | 0.170 | |
| Other | 0.331 | 0.029 | 0.294 | | 0.008 | 0.009 |
| Residential/commercial | 25.953 | 12.725 | 0.860 | | 12.368 | 4.102 |
| Residential | 15.472 | 7.435 | | | 8.037 | 2.399 |
| Space heating | 7.702 | 1.224 | | | 6.478 | 0.393 |
| Space cooling (A/C) | 0.657 | 0.657 | | | | 0.212 |
| Light | 0.816 | 0.816 | | | | 0.263 |
| Water Heating | 2.226 | 1.166 | | | 1.060 | 0.375 |
| Dishwashers | 0.127 | 0.127 | | | | 0.039 |
| Laundry | 0.272 | 0.233 | | | 0.039 | 0.075 |
| Cooking | 0.958 | 0.498 | | | 0.460 | 0.168 |
| Refrigeration | 1.717 | 1.717 | | | | 0.553 |
| Radio, TV | 0.636 | 0.636 | | | | 0.205 |
| Other | 0.361 | 0.361 | | | | 0.116 |
| Commercial | 10.481 | 5.290 | 0.860 | | 4.331 | 1.703 |
| Space heating | 3.098 | 0.170 | | | 2.928 | 0.055 |
| Space cooling (A/C) | 2.272 | 2.120 | | | 0.152 | 0.682 |
| Light | 2.162 | 2.162 | | | | 0.696 |
| Water heating | 0.352 | 0.042 | | | 0.310 | 0.014 |
| Cooking | 1.079 | 0.138 | | | 0.941 | 0.044 |
| Refrigeration | 0.382 | 0.382 | | | | 0.123 |
| Street lighting | 0.159 | 0.159 | | | | 0.051 |
| Water and sewer | 0.117 | 0.117 | | | | 0.038 |
| Government vehicles | 0.860 | | 0.860 | | | |

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