Efficient use of energy

At present our energy resources are being consumed with an appallingly low efficiency; examples drawn from automobile design, housing and industrial processing show where improvements could be effected.

The Study Group on Technical Aspects of Efficient Energy Utilization

Energy, it is becoming increasingly clear, is a precious commodity. Efforts are underway worldwide to seek new energy sources, to extend and conserve existing sources, and to educate consumers toward more intelligent use of the sources we have. We of this APS Study Group have been looking into the special contributions physics can make in the particular area of conservation by improved efficiency of energy-consuming devices. Here we present a brief summary of our report (see box on page 24). We have limited ourselves almost entirely to an analysis of the *technical* components of energy use,[1] rather than the regulatory, economic and persuasive tools that may be brought to bear on energy conservation[2]; our intention is to point out areas where scientists and engineers may contribute to the invention or improvement of the technical structure of the energy economy so as to provide new options, new opportunities and a more flexible basis for choice. (A listing of selected research opportunities appears on pages 32–33.)

By concentrating neither on energy *production* nor on *allocation* of energy among the different sectors of society, but rather on *end-use*, we have been able to examine the tasks ultimately responsible for the energy consumed. We have chosen three categories of end-use—the house, the automobile, and industrial processes based on chemical and physical changes of state—that form a nicely complementary set of cases for evaluating the ultimate technical potential for reduction of energy use.

The energy-consuming aspects of the services a house is asked to provide are, in the most general terms: warmth in winter; coolness in summer; hot water; light; food storage, and a means for cooking. To the extent that heat is lost in the winter and gained in the summer, and that we fail to take advantage of such natural aids as sunlight, solar heating and temperature averaging, the services are delivered inefficiently. We review in our report a number of suggestions on how heat loss (or gain) could be reduced. These include better insulation, increased heat capacity for thermal averaging, and better use of house aerodynamics and convective heat flow to minimize losses due to air infiltration and at the windows.

We found the automobile somewhat more difficult to evaluate, because much of the energy waste is attributable to social choice of transportation. But among our recommendations are that automobile efficiency could be improved considerably by better matching of the engine and transmission to the load, that energy dissipated in the brakes could be recovered and stored, that air-drag coefficients could be reduced, and that newly designed tire-suspension systems could yield large reductions in the power requirements of road vehicles.

Industrial processes may be classified into three general types: change in chemical state, change in physical state and fabrication. For the chemical processes not only is there critical technical work to be done to improve device efficiencies but also a considerable amount of basic research is needed on microscopic mechanisms—particularly those at surfaces. Important reductions in energy use in the physical-change processes could come through a better understanding of the mechanisms of separative processes, such as solute mobility and transport through membranes, and by the development of materials with better selectivity for different molecular species. Opportunities for improving fabrication efficiency are more difficult to generalize, but it appears to us that such opportunities do exist in specific processes.

Measures of efficiency

The first objective of any technical study of energy use is to establish a norm, a standard of performance against which present use of energy can be evaluated and a goal towards which technical innovation can strive. The discussion in most of the studies we have seen fall within the purview of the first law of thermodynamics, which is simply the conservation of energy, where "conservation" is now used in its physics sense. The use of the first law is inadequate for considering "minimum task energy," the minimum-energy path for performing a given task by means of any possible device or system. We know that energy is not lost; from the viewpoint of the first law, the task of minimizing energy consumption appears to be primarily one of hoarding. Yet we also know that, in any process involving heat, the constraints of the second law of thermodynamics, of the inexorable increase of entropy, usually guarantee that not all of the energy can be made available in useful form.

A quantity that we can call "first-law efficiency" is defined as

$$\eta = \frac{\text{desired energy transfer achieved by system}}{\text{energy input to the device or system}}$$

When the theoretical maximum value of this ratio is greater than unity, it is usually called a "coefficient of performance." When $\eta_{\max} \leq 1$, on the other

This article, prepared by PHYSICS TODAY with the assistance of Robert H. Socolow, contains material drawn from the report *Efficient Use of Energy: A Physics Perspective* written by Walter Carnahan (Hammondsport, N.Y.), Barry M. Casper (Carleton College, Northfield, Minn.), Kenneth W. Ford (University of Massachusetts, Boston; now at New Mexico Institute of Mining and Technology); Andrea Prosperetti (Cal Tech, on leave from University of Milan, Italy); Gene I. Rochlin (University of California, Berkeley); Arthur H. Rosenfeld (University of California, Berkeley); Marc H. Ross (University of Michigan, Ann Arbor); Joseph E. Rothberg (University of Washington, Seattle); George M. Seidel (Brown University, Providence, R.I.), and Robert H. Socolow (Princeton University).

hand, it is usually called an "efficiency."

We find a more useful measure of performance[3] to be the "second-law efficiency," defined for a device or system whose output is the useful transfer of work or heat (not both) as:

$$\varepsilon = \frac{\text{heat or work usefully transferred}}{\text{Maximum possible heat or work transferable}}$$

The denominator in this ratio refers to *useful* transfer of heat or work for the *same* function by any device or system using the *same* energy input as the given device or system.

As is obvious from this definition, the maximum value of ϵ is 1 in all cases. The numerator in the defining ratio is the same as for the first-law efficiency, but the "maximum" in the denominator now means the theoretical maximum permitted by the first and second laws of thermodynamics. Note that it is a *task* maximum, not a *device* maximum. The second-law efficiency provides immediate insight into the quality of performance of any device relative to what it could ideally be, showing how much room there is for improvement in principle. One limitation on the second-law efficiency, however, derives from its dependence on precisely how a given task is defined; some idealization and arbitrariness are inevitable.

Under certain circumstances, the first-law and second-law efficiencies can differ dramatically. For example, a furnace providing hot air at 110°F (43°C) to a house when the outside air temperature is 32°F (0°C) has a second-law efficiency $\epsilon = 0.082$ if its first-law efficiency is $\eta = 0.60$. For a power plant, on the other hand, the first-law and second-law efficiencies are nearly the same. Representative values of second-law efficiencies for most sectors of the US economy were estimated for our report and are presented in Table 1.

A very useful concept derived from these second-law considerations is that of "available work"; this is a quantity that has the dimensions of energy, yet is actually consumed in a process. There is an upper limit to the amount of ordered work energy that can be produced from disordered thermal energy at a temperature T_1 in a setting (typically the atmosphere) of fixed ambient temperature T_0. This upper limit, roughly, is the available work.

The further is the temperature T_1 from the ambient temperature, the greater is the amount of potentially available work. From the perspective of the second law, organized coherent motion is the most precious, very high (and very low) temperature heat is next most precious, and heat at a temperature near ambient (lukewarm, cool) is degraded energy. Good energy strategies aim to harness high temperatures, now often unusable because of materials limitations; they also aim to avoid degradation, by reducing thermal gradients, and by reducing the mixing of energy streams having substantially different temperatures.

This concept of available work appears in most engineering thermodynamic texts, often called "availability."[4] It permits a straightforward generalization of second-law efficiencies for devices providing both heat *and* work, and several examples are given in our report. The available work that can be extracted from an infinite heat reservoir at temperature T_1 is the familiar fraction $(T_1 - T_0)/T_1$ of the heat that flows to the environment at temperature T_0. Water heating, space heating and air conditioning are all much further from the thermodynamic ideal than the usual measure of "efficiency" reveals, because they are all associated with small percentage changes in absolute temperature. Thermodynamics permits relatively small amounts of chemical energy, electricity, or other forms of high-quality energy to transfer large amounts of heat through small temperature differences.

To assign a second-law efficiency to any type of energy use on a national scale is possible in principle, although of course difficult in practice. In Table 1 we show very rough estimates of ϵ for major energy uses in the US. We consider the overall perspective provided by a table such as this to be valuable; despite the uncertainties in some of the entries, the table emphasizes the fact that there is room for great improvement in most areas. Transportation and low-temperature use of heat are notably inefficient.

There are, of course, technical as well as economic obstacles, some of them formidable, that prevent the achievement of second-law efficiencies close to unity. In economic terms, there may be no *reason* to press for efficiencies beyond a certain level. Nevertheless, as physicists, we must think in terms of what Nature permits.

Organization and publication

From an ad-hoc meeting organized by The American Physical Society, held in August 1973 at Los Alamos, N.M., grew proposals for three studies of physics problems related to energy technologies. The studies were on "Light-Water Reactor Safety" (summarized in PHYSICS TODAY, July, page 38), on "Radiation Effects in Materials" (to be reported in PHYSICS TODAY in the September issue) and on "Technical Aspects of Efficient Energy Utilization," the subject of the present article.

This APS-sponsored summer study on efficient use of energy was held at Princeton University during July 1974, with support from the National Science Foundation, the Federal Energy Administration and the Electric Power Research Institute. About forty physicists and engineers attended. Three parallel and independent substudies were conducted, each group preparing its own report; their subjects were, respectively: Research Opportunities; Combustion, and Windows and Coatings. The main part of the accompanying text is PHYSICS TODAY's summary of the report prepared by the Research Opportunities subgroup (principal investigators, Marc H. Ross and Robert H. Socolow). The box on pages 26–27 is a brief account of the work of the Windows and Coatings subgroup (principal investigator, Samuel M. Berman, Stanford). An article to appear in PHYSICS TODAY later this year will summarize the report of the Combustion subgroup (principal investigator, Dan Hartley, Sandia). An APS Review Committee consisting of Luis Alvarez (University of California, Berkeley), Alan Chynoweth (Bell Laboratories) and James Comly (GE), received and reviewed the reports of all three subgroups.

The reports of all three subgroups will be published in the AIP Conference Proceedings series. The Research Opportunities report alone may also be found included as an appendix to the published version of the 18 February Hearings Before the Subcommittee on Energy Research, Development and Demonstration of the House Committee on Science and Technology.

Energy indoors

One section of our report describes the furnace, the water heater, and several other energy systems in the house. "House" is used here as shorthand for any dwelling unit, including apartments, row houses and detached houses; there are 60 million such dwelling units in the US. A Stanford Research Institute compilation[5] indicates that 18 percent of the US energy consumption in 1968 went to space heating, 4 percent to water heating and 2.5 percent to air conditioning (residential and commercial sectors combined).

The most significant environmental parameter for energy consumption in a house is, of course, the average daily outside temperature. The next most important parameter is wind speed. The effects of wind speed on energy consumption in a house are only now being studied, and it is becoming clear that wind dominates the dynamics of the exchange of air between inside and outside, known as "air infiltration." One-third or more of the total heat loss from the interior of the house is associated with this convective exchange with outside air.

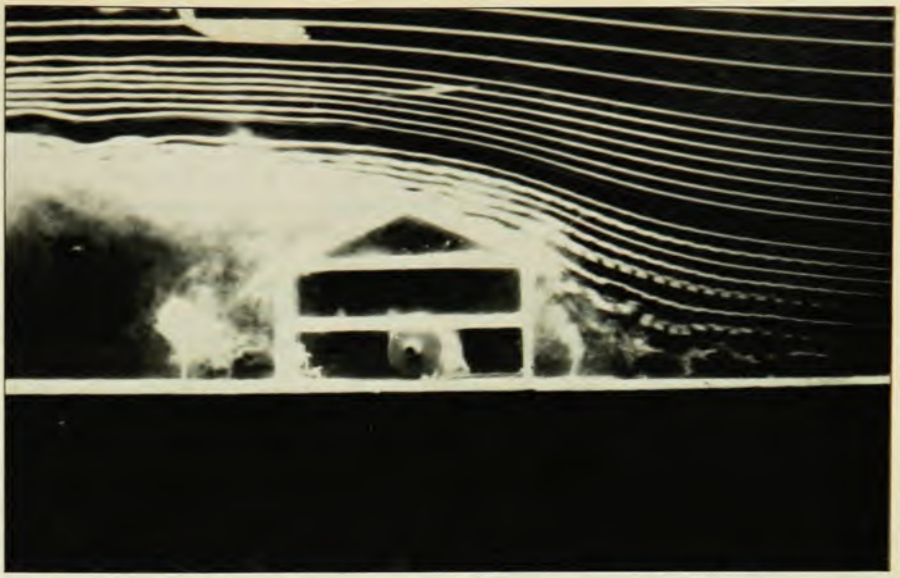
The solar energy incident on an unshaded house on a clear day in winter, averaged over day and night, is comparable to the energy required to heat a typical house on the coldest day in an average US location. But winter sun is largely decoupled from the interior environment of a house today. The sun is a more critical environmental parameter in summertime, because the typical temperature difference between outdoors and indoors is rarely more than 20°F (11°C). This is one reason why no "cooling degree day" measure based on temperature alone is as reliable a predictor of energy consumption as the "heating degree day."

Other environmental parameters of a site illustrate opportunities for interaction between house and surroundings. Ground water undergoes little fluctuation in temperature over a season, being part of a system whose time constant is measured in years and hence reflects an average yearly temperature; in many situations ground water has attractive possibilities as a component of heating and cooling systems. Other ideas involve passive components, such as high heat-capacity systems, to take advantage of a comfortable *daily average* temperature in summer.

Another type of opportunity for economy involves locating the crucial stage of energy conservation at the site of its end use. One suggestion is that fuel-based heating systems might be best controlled, and operated with reduced flue and duct losses, if fuel could be burned catalytically at low temperature in room radiators. The catalytic combustion is not in itself an efficient process in the second-law sense; but the advantage of location might mean a system with overall improved efficiency compared with present furnace-based systems. There are more mundane and perhaps more important examples of this principle—such as spot water heaters at the dishwasher, say.

Both air conditioners and furnaces are usually designed to run intermittently at full capacity, with a capacity chosen to handle the severe weather of "design conditions"—conditions that are met or exceeded, typically, only about 50 hours per year. The advantages and disadvantages of running more nearly continually at reduced output in more typical winter or summer weather do not appear to be well understood from a theoretical standpoint.

One particularly important aspect of energy use, especially electricity use, is the time dependence of demand. Minimum demands occur during spring and fall. In some areas with cold winters and much electric heating equipment, the maximum peak load occurs during the winter, while in some other places (New York City is one of the more extreme examples) the peak occurs on hot summer afternoons. Any changes that could be made in the methods of air conditioning to reduce electricity demand during peak hours would be most important. Such changes might include increased heat capacity of the house, changeover to other fuels, more efficient cooling cycles, energy storage,



Wind-flow patterns around a house. The effects of wind speed on energy consumption in a house are only beginning to be studied, with results showing their importance in air-exchange dynamics. This photograph of a house model was made by George Mattingly in the smoke tunnel of the aerospace and mechanical sciences department on Princeton's Forrestal campus.

improved architectural design, use of shading and reflecting materials, cooling with ground water, among other ideas.

In our report we look more quantitatively than we can here at the opportunities we see for improved energy utilization. First we attempt to give a sense of the magnitudes of the various energy gains and losses in the winter heating of a typical house in an average climate. Then we examine important components and subsystems relevant to energy use, including lighting, and continue with a detailed discussion of water heating, space heating and air conditioning viewed from the standpoint of the second law of thermodynamics (see Table 2). And finally we look at the opportunities and obstacles related to producing low-temperature heat and electricity in combined systems.

Our conclusions and recommendations for further technological improvements include both system-design suggestions and research that could lead to new design; examples of what we have in mind are included in the list of research opportunities that appears on page 32. In general we emphasize throughout this section that dramatic improvements in the performance of ac-

Table 1. National perspective on efficiency of energy use

Use	Percent of US fuel consumption (1968)*	Estimated overall second-law efficiency ϵ
Space heating	18	0.06
Water heating	4	0.03
Cooking	1.3	—
Air conditioning	2.5	0.05
Refrigeration	2	0.04
Industrial uses		
process steam	17	~0.25
direct heat	11	~0.3
electric drive	8	0.3
electrolytic processes	1.2	—
Transportation		
automobile	13	0.1
truck	5	0.1
bus	0.2	—
train	1	—
airplane	2	—
military and other	4	—
Feedstock	5	—
Other	5	—
	100	

*Sources: Stanford Research Institute (ref 5) and Mitre Corporation, report no. 6577 (1973).

tive systems in the house are possible *in principle*, as Table 2 shows. But to realize these improvements in practice needs, in addition to the specific research topics listed, better empirical data on virtually all components of the energy-consumption system and better and more complete mathematical modelling programs.[6]

The automobile

Fuel consumption for transportation amounted to almost 25 percent of the total US energy consumption in 1970. More than half of this energy was directly consumed by automobiles. When we add the direct fuel cost for trucks and buses we find that the rubber-tired, internal-combustion-engine-powered highway vehicle has a direct fuel consumption that accounts for about 18.5 percent of the total US energy consumption and 40 percent of its petroleum. The opportunities for energy savings in this sector by technical means alone have been estimated[7] at 25 to 30 percent, a figure we regard as conceptually conservative.

The section of our report dealing with the automobile opens with a detailed power-train analysis for the internal-combusion-engined vehicle. The analysis takes into account the combustion losses in the Otto-cycle engine, frictional losses, transmission losses and energy consumption by accessories; the overall efficiency for converting the flow of fuel energy to the engine into power delivered at the driving wheels is the product of factors determined for all these steps (see Table 3). We find that the second-law efficiency of a relatively light and low-powered US compact car, operated on the Federal Urban Driving Cycle, is only 0.08.

The energy delivered to the rear wheels is used to accelerate the vehicle, to climb grades, and to overcome resistance to motion. This energy must, however, ultimately be dissipated as heat to the road and to the air; the three primary loss mechanisms are the brakes, air resistance, and the rolling resistance of the tires. An estimate[8] of the energy dissipated by the brakes, compared with the total work done at the rear wheels, suggests that 32 percent is lost in urban driving, 10 percent in suburban and 2 percent in highway driving. The rest of the energy is used to overcome air resistance (very little in the Urban Driving Cycle) and rolling resistance (which accounts for ⅓ to ½ of the total energy delivered to the driving wheels).

Our report considers at some length ways of increasing power-train efficiency, including the use of novel fuels, different engines, recovery and storage of kinetic energy and better engine-load matching, together with other improvements such as reducing the mass and air resistance of the vehicle, and the effects of redesigned and improved tires, suspensions and accessories.

Reduced combustion temperatures and better combustion could allow the Otto engine to run at reduced HC and NO_x emission levels. The use of emulsions of normal fuel with water or methanol might possibly accomplish this goal, while simultaneously decreasing the fuel-air ratio at which reliable performance is obtainable—this decreased ratio would also increase engine efficiency above currently obtainable values. Ethanol and methanol appear to be the most promising candidates for new fuels that might become cheaper and more widely acceptable than petroleum by the end of the century.

The Otto cycle might be improved with better combustion in a stratified-charge design, with 25–30 percent savings over comparable future Otto-cycle engines (whose efficiency is expected to be lowered by new emission standards) or 5–10 percent savings over current engines. We also consider the Diesel engine; a well-designed Diesel has a net efficiency at full load 20–30 percent greater than that of the comparable Otto-cycle engine, is more fuel-adaptable than the Otto, and no fuel-supply problems are anticipated other than those due to general petroleum shortages.

Advanced engine cycles well worth the physicist's attention include the Rankine and Stirling cycle external

Energy conservation and window systems

The subgroup of the APS study on technical aspects of efficient energy utilization that was concerned with window systems had eleven members: Samuel M. Berman (Stanford): A. S. Barker (Bell Labs); Philip Baumeister (University of Rochester); David Claridge (Stanford); F. Howard Gillery (Pittsburgh Plate and Glass); M. M. Labes (Temple University); Robert Langley (Engelhard Mineral and Chemical Corp.); Henry Mar (Honeywell); Leonard Muldawer (Temple); Steve Schnatterly (Princeton), and Seth Silverstein (GE). Berman (the principal investigator) and Silverstein were the editors of the report.

The summary presented on these two pages was prepared by PHYSICS TODAY from material contained in this group's report.

The report of this subgroup is an assessment of the role of the architectural window as an important factor in reducing energy consumption for residential and commercial climate control. It evaluates the cost-effectiveness of many existing and modified window systems. Some of the suggestions, if implemented, would reduce energy consumption while maintaining high esthetic standards.

The report stresses, with quantitative examples, that during the space-heating season the solar energy transmission through windows is a significant positive source of fuel-free energy. The window acts like a low-temperature solar collector and, if it is properly designed, the winter heat solar gain (weather averaged) will exceed the thermal losses for east, west and south-facing windows over most of the continental US.

Constantly drawing the analogy between the window and the low-temperature solar heat collector, the report shows that all heat-transfer analyses, cost-effectiveness analyses, discussions of new materials and innovations have applications to various aspects of the solar heat collector problem.

In the complete report is an assessment of the physics and technology of selective coating materials, which act primarily as infrared reflectors to reduce thermal radiation transport, and a review of properties of presently existing selective surface materials. The report closes with a discussion of recommended research directions for the development of new materials and laminates.

Some statistics. Space heating in the US accounts for 21% of the total national energy consumption, and of this 21%, three-fifths is for residential heating, two-fifths for commercial. A reasonable estimate of the percentage of the national energy consumption corresponding to space-heating loss through architectural windows is about 5%.

The thermal losses through windows are offset to a certain degree by solar gain, the amount depending on latitude, climate and window orientation. The solar heat gain makes some windows better in the net energy balance than the best insulated walls. Of the 5% of the national energy consumption lost through windows, less than half is "cost-effectively" recoverable with better insulated window systems and summer shading. On a national basis, a third to a half of the thermal heat losses through windows are compensated by solar gains during the heating season.

Energy-transfer mechanisms. The significant energy-transfer mechanisms through an architectural window are: thermal heat-transfer losses (coupled conduction–convection, thermal radiation); solar influx (which is approximately independent of the indoor–outdoor temperature difference), and infiltration (leakage due to air gaps).

The report gives the results of detailed window calculations for variable window geometries, different construction materials and weather factors. The variables considered individually and in combination are:

- Variable-emissivity surfaces to reduce thermal radiation transport. These emissivities cover the full range available to doped semiconductor or metallic films.
- Effects of multiple glazing (storm windows, double glazing, and so on).
- The effects of gap thicknesses in multiple glazing.

combustion engines; the Brayton-cycle gas turbine does not appear to hold much promise for automobile use at the moment, and the rotary Wankel engine has suffered some setbacks (notably because of poor fuel economy). We do not deal at length with electric propulsion systems, primarily because they have been particularly well studied recently[9]; however we believe they warrant further investigation.

Mechanical energy storage systems, such as flywheels, appear (with present materials) to have only restricted applications as prime movers for vehicles. But some system for recovering kinetic energy—say by using generators as vehicle brakes—has some potential as a supplement to existing energy sources. Conceivably the energy consumption in Federal-Urban-Cycle driving could be improved by as much as a factor of two in this way.

Smaller engines operating normally at higher load factors are more efficient than today's large and under-used engines. We consider that a small engine provided with a demand "boost" (supercharger, exotic fuel, or supplementary power system) for occasional needs could increase fuel economy by 15 percent, even if vehicle weight were unchanged.

Redesign effort would be worthwhile in the areas of reducing vehicle mass, reducing air resistance and improving tires. Various tire improvements appear possible, but always there are safety considerations too; a worn tire has far less rolling resistance than when it is new but quickly becomes unsafe as wear progresses.

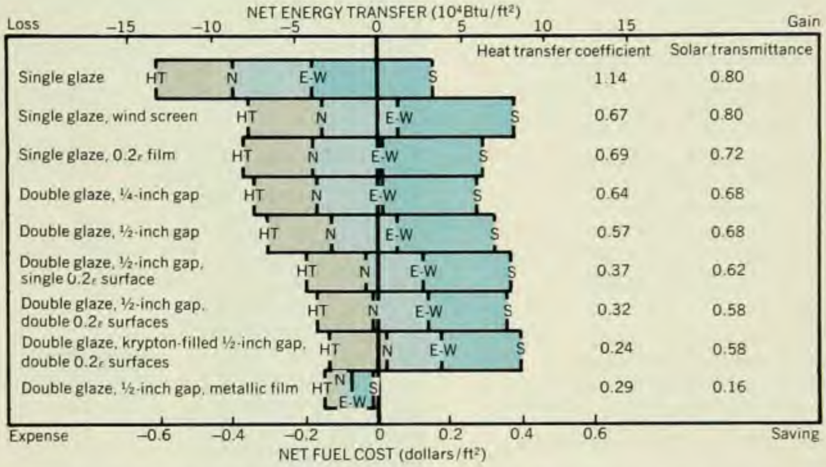
We conclude this section of our report with a summation of the possible economies that could be effected with appropriate redesign.[10] We show, first, a modest, presently feasible, redesign of the private automobile that would operate with a top speed unchanged from present standards, acceleration down by 20 percent and a savings of 33 percent over present gasoline consumption. And secondly we outline what we call a "less modest" proposal: a hypothetical, yet reasonable, vehicle for the 1980's and beyond that uses less than half the fuel of today's automobiles while turn-

▶ Gaps of multiple-glazed units filled with heavier molecular-weight gases to reduce convection. Here it is shown that this option is effective only when coupled with low-emissivity surfaces.

▶ Effects of wind velocity, which drives the forced convective losses at the exterior window surface.

Cost-effectiveness. The report's analyses of the potential solar heat gain through architectural windows include considerations of various seasons, various geographical locations representative of latitude and weather, and various window directional orientations. The most significant results are that the solar influx through windows represents a very beneficial fuel-free energy source for auxiliary space heating, and that the capital costs required to make windows better than insulated walls in conserving energy are not high. These results have an important bearing on prospective energy-conservation legislative codes, some of which seek to restrict the glass area of buildings in the belief that energy will be saved thereby.

An example of a cost-effectiveness analysis for nine different window systems is shown in the figure. From charts such as this, comparisons can be made of fuel savings versus capital expense for various window systems in different locations and orientations, to see whether a proposed "improvement" in a window system would be worthwhile.



Energy-transfer balance for various window systems. This analysis is given for the New York City climate, with fuel costs at 40 cents/gallon of fuel oil and a furnace efficiency of 67%. The heating cost is thus \$4.60/MBtu. On the bar for each window system, "HT" represents the direct heat transfer lost, and N, E-W and S show the net energy transfer for window orientation in each of the four cardinal directions. Net energy transfer and net fuel cost scales are for the entire heating season in one winter of the New York City climate. Heat transfer coefficients are shown on the right in units of Btu/hour-ft^2-°F in a 12-mph wind. The complete report of the APS summer-study group includes worked examples, drawn from this figure combined with additional information on capital expense and depreciation, that compare cost-effectiveness in different cases.

Selective surface materials. Selective infrared-reflecting coating materials have broad application to many energy-storage systems where thermal radiative losses are significant. In architectural windows, very low cost and high film-thickness uniformity are required to achieve significant consumer utilization. In solar heat-collector windows, on the other hand, high transmission of the solar irradiance is mandatory, while iridescence is of less concern.

The review of presently available selective surface materials in the report includes discussions of the properties of, and deposition techniques for, the doped wide-band-gap semiconductors such as SnO_2:Sb; SnO_2:F, and In_2O_3:Sn. Materials such as these are in common use today to increase the efficiency of low-pressure sodium lamps by infrared reflection. They are also widely used in the electronics industry for transparent contacts in photoactivated devices. The infrared reflectivity and high electrical conductivity both arise from the same mechanism of high mobility-free carriers introduced by impurity doping. Discussion is also given of various metallic films that are marketed primarily with the objective of reducing summer solar heat gain while air conditioning is required. In the survey of the plastic-metallic film laminates that are presently marketed, stress is laid on the hoped-for low emissivity properties of such laminates, which are most often negated by the infrared absorptions of the plastic covering material.

Plastic laminates have considerable potential for architectural windows—they could be easily cut and fitted to existing windows—and for solar-collector windows, where weight loading due to glass is often of great concern. But for the latter application, polymers must be chosen that would not be subject to ultraviolet degradation.

The final section of the report deals with the basic physics of selective infrared reflecting wide-band-gap semiconductors. The mechanisms for the infrared reflectivity are discussed to identify the significant electronic parameters that lead to the desired selective characteristics.

An extensive search of most known semiconductor materials, made with the objective of finding new candidate materials that exhibit the desired selective surfaces, has resulted in thirteen possible materials being identified on which further research is recommended. The thirteen candidates are: CaB_6, CuCl, CuI, MnO, NiO, SiN, S, ZnO, ZnS, TiO_2, Sb_2P_3, PbO and Bi_2O_3.

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Table 2. Efficiencies of household energy systems

Household task	Ambient temperature T_0 [°F(°C)]	Task temperature T_2 [°F(°C)]	First-law efficiency η	Second-law efficiency ϵ
Hot-water heating				
Electric	55 (13)	120 (49)	0.75[a]	0.015
Gas	55 (13)	120 (49)	0.50	0.029
Space heating				
at the room	40 (4)	70 (21)	0.60	0.028
at the register	40 (4)	110 (43)	0.60	0.074
at the furnace plenum	40 (4)	160 (71)	0.75	0.145
Air conditioning	90 (32)	55 (13)	2.0[a,b]	0.045

[a] The first-law efficiency is a factor 3 smaller if one refers back to the fuel at the electric power plant. (To compute the second-law efficiency, one *must* refer back to the power-plant fuel.)
[b] Coefficient of performance.

ing in a similar speed and acceleration performance.

Industrial processes

In our complete report, while admitting that a detailed discussion of all types of industrial processes is beyond the scope of the study, we look at a few selected topics that appear to have some generality with respect to energy use and should therefore be high on a list of research priorities.[11] Our focus is on basic research opportunities in electrochemical processes, in the physical separation of materials and in heat transfer.

The transformation of chemical energy to electrical energy converts the energy associated with the charge distribution in molecules to energy in the form of a guided electromagnetic wave. Traditionally the most economical ways of doing this have been through intermediate steps of uncontrolled combustion—a testimony to our lack of understanding of many of the mechanisms occurring in molecular interactions. The suggestion that the transformation could be better performed in a "fuel cell"—in which reactants combine directly to produce electricity without the loss of available work in combustion and heat-engine stages—goes back at least 80 years, yet we are still looking for a way to do it economically.

Physical descriptions of phenomena in the field of electrochemistry have generally tended to follow industrial application, rather than the other way around. Our present understanding, as a result, is rather empirical when viewed in a physics perspective. For the fuel cell the single most important phenomenon is electrochemical charge transfer—and a basic description of this process has not yet been developed.

Among experts in the field of fuel-cell technology the general opinion is that a practical, commercial device will be developed by incremental advances with another decade of hard work. It would appear that physicists have a major opportunity to contribute through basic science to this end.

As well as providing the impetus for fuel-cell development, the space program has also directed attention over the last twenty years to the conversion of solar energy to electric energy in photocells. At present the cost of electricity from photocells is prohibitively high; recent progress in fabricating large silicon crystals[12] will lower costs, but further advances are needed to make the solid-state photocell competitive.

Possibilities in the conversion of solar energy directly to chemical energy are not as well known to physicists. Photosynthesis is one such process, but so far no other mechanisms have been found that improve on Nature. Some work following that of L. J. Heidt[13] is in progress on the photolysis of water with the aid of an inorganic catalyst, and an observation[14] of photodecomposition of water at a semiconductor surface looks promising.

More efficient use of energy in society could well depend on improvements in the technology of rechargeable batteries—consider, for example, the many proposals for electric automobiles, each relying on storage batteries for portable power. At the moment the lead-acid battery is too heavy to be practical for this purpose; the further development of batteries with lightweight electrodes would change the outlook considerably.

Turning to physical processes in industry, we next consider the separative processes in two broad groups: macroscopic (filtration of precipitates, recycling of materials in mixed waste streams), and microscopic (separation at the molecular level). In the first group we expect improvements in energy use to derive more from technology rather than from basic science. Examples of the second group that we consider in some detail are the production of oxygen by separation from air and the desalination of sea water.

In a concern for the efficient use of energy we note that the minimum work required to separate chemically nonreacting constituents of a system is $T\Delta S$, where T is the absolute temperature and ΔS is the entropy of mixing. In many cases, especially in dilute systems, latent heats may be very much larger than the minimum work $T\ \Delta S$; although much of the energy required to change the temperature and produce the phase transition may be recoverable with the proper use of heat exchangers, such processes rarely approach efficiencies close to unity. The best solution to many molecular-separation problems is often not to employ a phase change but rather to make use of other physical processes, such as diffusion, adsorption, osmosis or ion exchange. The selectivity of these processes to different molecular species makes them very attractive. Notwithstanding the long history of successful use of such processes in industry, better basic physical understanding and improved techniques hold promise of substantially improving their efficiency.

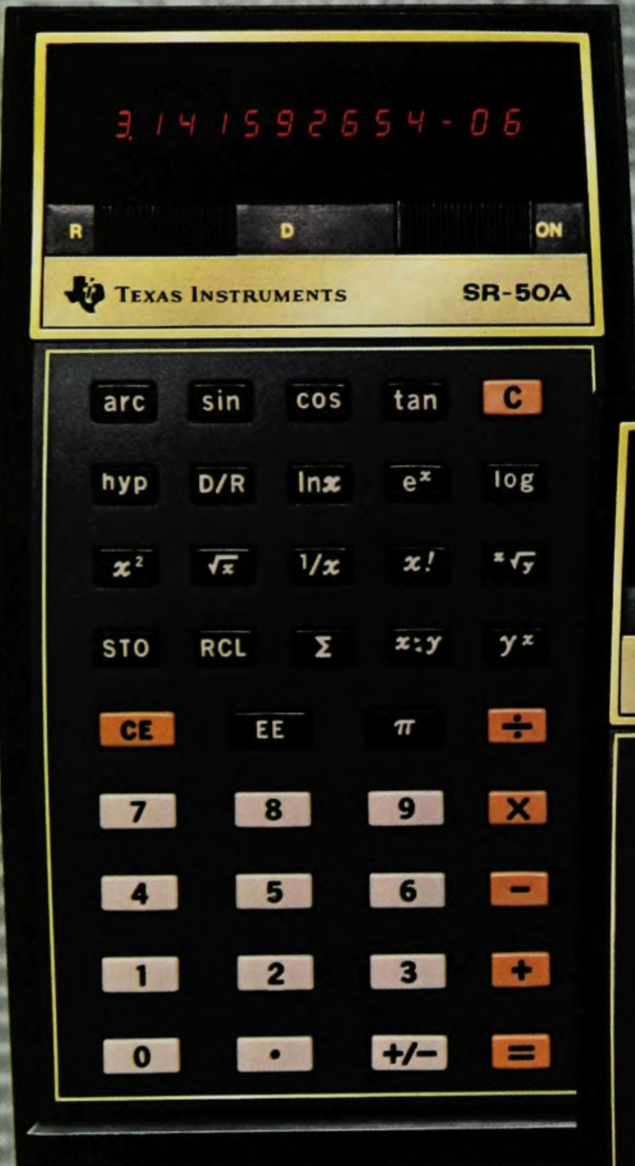
Desalination of sea water provides a striking illustration of the differences in

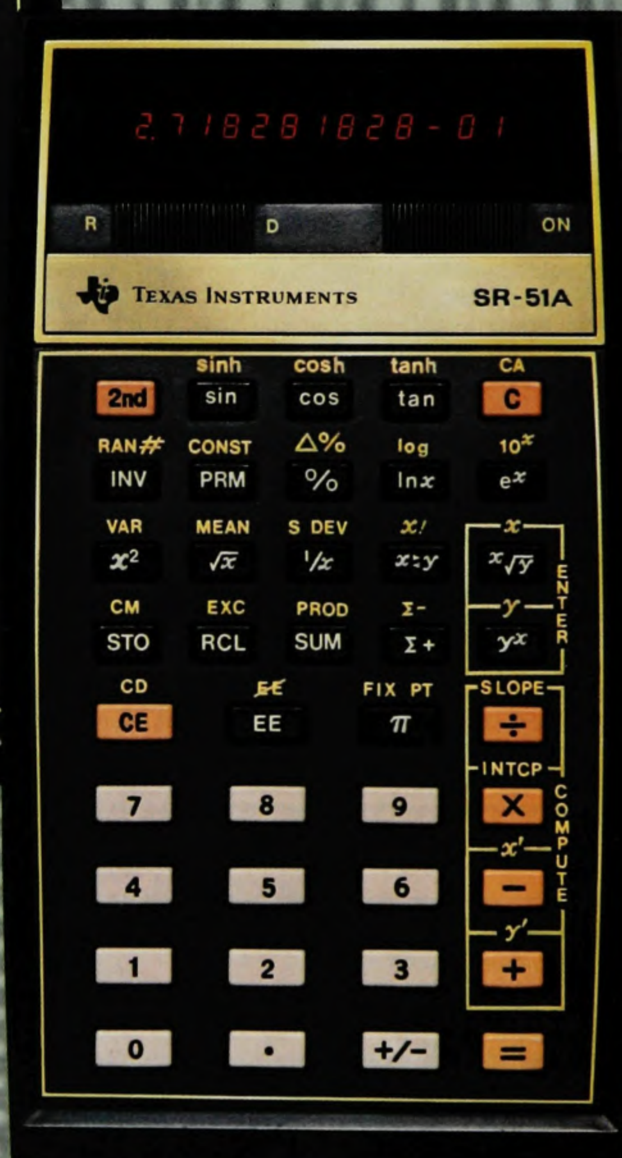
Table 3. Automobile energy flow

Fuel available work		100%
Fuel energy (commonly used lower heat of combustion)	× 0.96	96%
Ideal gas air-cycle Otto engine, compression ratio = 8	× 0.56	54%
Fuel-air Otto-cycle, stoichiometric	× 0.75	40%
Burning and cylinder-wall losses	× 0.8	32%
Frictional losses	× 0.8	26%
Partial load factor (estimated)	× 0.75	19%
Estimated loss due to accessories (including air conditioner)	*	11%
Automatic transmission (estimated)	× 0.75	8%
Net output to rear wheels (efficiency)		8%

Data for a 2500-lb automobile over the Federal Urban Driving Cycle: from J. T. Kummer, *The Automobile and the Energy Crisis*, Ford Motor Co., Dearborn, Mich. (1974).
* Not necessarily expressible as a multiplier

The SR-50A. The SR-51A.





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Selected research opportunities

The list of research opportunities below contains problems and areas that we found interesting, but it is surely incomplete. Those within the scientific and technical community who are concerned, individually or collectively, with energy efficiency will add additional ideas and will judge the ripeness of the various opportunities.

Second-law efficiency

Systematic investigation of points of entropy increase in energy-using systems

Calculations of second-law efficiencies for industrial processes with a view to identifying the most fruitful areas for technical improvement

Systems studies of the cascading of heat energy in specific industries

Classification of processes according to the minimum required energy quality with a view to better matching of energy source and energy use

Interdisciplinary investigation of more sophisticated procedures of energy and entropy accounting

Energy indoors

Energy management

Studies of heat transport over long distances (including heat transported as chemical potential energy)

Systems analysis of district systems to supply both heat and electricity to a building or a group of houses

Systems studies of house-scale heat and electricity systems based on fuel cells (possibly ones deliberately chosen to have low electric efficiency)

Extensive data gathering and modeling of energy-use patterns of existing houses and buildings of various types

Research on heat storage for better load averaging of both solar and electric power

Thermal properties of buildings

More flexible computer modeling to include the effect of wind

Measurement and modeling of thermal response functions of buildings

Investigation of building materials with large specific heats

Theoretical and experimental studies of external features, including sun control and surfaces of variable reflectivity

Insulation

Theoretical modeling together with experimental studies to select new materials and filler gases, to control cell size, and to enhance fire resistance

Investigation of a "thermal diode"

Development of layered material with variable, controllable conductivity

Development of window coatings to control heat loss

Optimization of insulation for the distribution of space heat

Aerodynamics

Outside: studies of micrometeorology, wind effects on heat transfer and infiltration, control of local air flow patterns

Inside: development of methods to control air flow, especially near walls, windows, and ducts

General: microscopic studies, experimental and theoretical, of heat transfer at solid surfaces bounded by moving air

Air conditioning

Broad search for new techniques using heat to power air conditioners; experimental studies of absorption and adsorption cycles

Search for new desiccants, especially with a view to lowering the regeneration temperature

Systems studies of ground-water cooling

Interdisciplinary studies of ground-water hydrology for heat-transfer applications

Space heating

Continued research on heat-pump cycles and technology to extend the useful temperature range

Systems studies of solar-assisted heat pumps

Systems studies (and hydrology) of using ground water as the low-temperature reservoir of a heat-pump system

Basic heat-transfer studies at solid-fluid interfaces, with a view to decreasing ΔT across heat exchangers working not far from ambient temperatures

Hot water

Detailed measurements and modeling of patterns of hotwater heating and use in houses and buildings

Systems studies of heating or "boosting" water at the point of use

Continued development of solar hot-water heating systems

Lighting

Basic research on gas discharges and on fluorescence with a view to increasing the efficacy of light sources and controlling the color

Development of small and/or screw-in fluorescent lamps (mostly engineering)

energy expenditures by different separation processes. Desalination is an insignificant user of energy at present, but the social and political implications of an inexpensive method for desalting water are staggering to contemplate. The separative work required to convert sea water at 3.5 percent salinity and 20°C to half fresh water and half brine with twice the salinity is 0.97 kilowatt hours per cubic meter of fresh water produced, or 3.5 kJ/kg.[15] This number is very much less than the heat of vaporization of water, 540 cal/gm (2300 kJ/kg), or heat of fusion, 80 cal/gm (330 kJ/kg). Present technology with multistage evaporators requires a thermal energy input of the order of 280 kJ/kg, whereas present freezing processes use about 60 kJ(electric)/kg, equivalent to about 180 kJ(thermal)/kg.[16] Combination of electric power generation and water desalination into a single plant can cut the energy requirements assigned to the desalination process, but only by a factor of about two.

The transport of molecules and ions in inhomogeneous systems such as membranes, the distribution and aggregation of molecules in solution, on surfaces and in membranes, the relationship between the nature of adsorbate and adsorption phenomena, the energetics of biological membranes and the kinetics of ion exchange are but a few of the areas in which future research can have an important impact on our energy consumption.

In the closing section of our report we look at research needs in heat-transfer processes. By considering examples drawn from such areas as convection, change-of-phase, conduction and radiation processes, two-phase flow and heat transfer near the critical point (in a discussion based largely on studies by R. H. Sabersky[17]) we were able to identify particular research needs that physicists might be able to fill. They include basic research in fluid mechanics, surface physics, nucleation theory, optical and infrared emission and absorption, and the computation and measurement of transport coefficients and material properties (particularly under unusual conditions, such as at high temperature or pressure, or near a critical point).

A thought for the future

Scientists attacking problems of energy efficiency require facility in subjects of classical physics—such as fluid dynamics and thermodynamics—that are all too often neglected in our educational institutions. These subjects need renewed emphasis; they can offer challenge and satisfaction to students and teachers alike.

We believe that the concepts of second-law efficiency and available work, and the resulting systematic organization by process and task rather than by industry and device, offers new and powerful tools in areas where research

Development of efficient kHz power supplies and further studies of frequency-dependence of fluorescent-lamp efficacy

Interdisciplinary studies of lighting needs for various tasks—intensity, uniformity, spectral distribution

Exploration of more effective ways to use sunlight indoors

Instrumentation

Development of easy-to-use local heat flux meter

Development of cheap home instruments for monitoring and control, such as a clock-programmed thermostat, a degree-days-per-gallon meter (with suitable time averaging), on-line monitor of furnace burner efficiency

Packaging of a meter to measure air exchange rate in a room or a building

The development for larger buildings of on-line monitoring of several features of air quality coupled with control of reconditioned air vs. fresh air; the development of devices to recondition air

Development of infrared equipment for diagnostic studies of houses

The automobile

The power plant

Basic studies of the combustion process; development of advanced combustion diagnostic techniques

Continued research on external combustion engines (Rankine, Stirling)

Continued research on small diesel engines, to reduce their weight, noise, smoke and odor

Studies of a variety of hybrid power plants (small internal-combustion engines plus a source of boost power)

Extended studies of fuel emulsions and novel fuels

Energy storage

Further systems studies of harnessing braking energy with a dynamotor

Basic research on rechargeable batteries (see electrochemical processes, below)

Experimental and theoretical studies of flywheel storage

Weight

Exploration of lighter automobile structural materials

Studies of the crashworthiness of lighter (not necessarily smaller) cars

Air drag

More elaborate studies, experimental and theoretical, of automobile (also truck) air drag, including the effect of relative motion of the vehicle belly and the road

Tires and suspension

Basic studies of viscoelastic materials and exploration of radically new tire designs

Exploration of tradeoffs in function among tires, wheels, and suspension, with a view to increasing the role of the suspension and decreasing that of the tire, to preserve ride and safety while decreasing rolling resistance

Instrumentation

Development of a sophisticated yet inexpensive miles-per-gallon meter capable of integrating over various times or distances

Implementation of other monitoring meters of engine efficiency, fuel flow, automatic-transmission gear

Accessories

Development and refinement of heat-powered air conditioners for automobiles and trucks

Industrial processes

Electrochemical processes

Basic research on the physics of charge transfer at electrolyte–electrode interfaces

Basic physical studies of the principles of solid electrolytes

Continued search for rechargeable batteries of greater energy density

Basic research on all aspects of surface phenomena, especially as applied to fuel-cell performance

Photochemical processes

Exploration of catalyzed solar photolysis of water

Continued studies of the semiconductor physics of photovoltaic cells

Physical processes

Studies of adsorption techniques for molecular separation

Basic research on transport in membranes

Careful studies of the energy inefficiences in ore beneficiation and water desalination to seek ways to approach more closely the minimum separative work

Heat transfer

Basic studies of heat transfer at interfaces—the role of convection, the role of surface irregularities

Basic studies of boiling

Fundamental investigation of two-phase flow

payoffs can be large. At present, our energy resources are being consumed with an overall second-law efficiency of only 10–15 percent. This is not only wasteful; it is *inelegant*. There is much room for improvement, for designing our machines to be technically excellent and to reflect the powerful insights of modern science and technology.

References

1. For an earlier study, see *Technology of Efficient Energy Utilization* (E. G. Kovach, ed.), report of a NATO Science Committee Conference held at Les Arcs, France, 8–12 Oct. 1973. (Available from Pergamon Press, New York, 1975.)
2. Energy Policy Project of the Ford Foundation: *A Time to Choose*, and *The Energy Conservation Papers* (R. Williams, ed.) both published by Ballinger, Cambridge, Mass (1975).
3. C. A. Berg, "A Technical Basis for Energy Conservation" in Technology Review, Feb. 1974, page 14; and J. H. Keenan, E. P. Gyftopoulos, G. H. Hatsopoulos, in *Proceedings of the MIT Energy Conference* (M. S. Mackrakis, ed.) MIT Press (1973).
4. J. H. Keenan, *Thermodynamics*, Wiley, New York (1948).
5. *Patterns of Energy Consumption in the United States* (prepared by Stanford Research Institute), US Office of Science and Technology (1972).
6. For additional discussion see R. Schoen, A. S. Hirshberg, J. M. Weingart, *New Energy Technologies for Buildings*, Ballinger, Cambridge, Mass. (1975).
7. *Research and Development Opportunities for Improved Transportation Energy Usage*, summary report of the Transportation Energy Panel, report no. DOT-TSC-OST-73-14, US Dept. of Transportation (1972).
8. J. T. Kummer, Technology Review, February 1975, page 26.
9. *An Evaluation of Alternative Power Sources for Low-Emission Automobiles*, Nat. Acad. Scis., Washington D.C. (1973); *Automotive Research and Development and Fuel Economy*, Hearings before the US Senate Committee on Commerce serial no. 93-41, US Govt. Ptg. Office (1973), and ref. 7.
10. See also J. R. Pierce, Scientific American, January 1975, page 34.
11. See also E. P. Gyftopoulos, L. J. Lazaridis, T. Widmer, *Potential Fuel Effectiveness in Industry*, Ballinger, Cambridge, Mass. (1975).
12. A. L. Hammond, Science **184**, 1359 (1974).
13. L. J. Heidt, Proc. Amer. Acad. Arts and Scis. **79**, 228 (1951).
14. A. Fujishima, K. Honda, Nature **238**, 38 (1973).
15. J. Harte, R. Socolow, *Patient Earth*, Holt, Rinehart and Winston, New York (1971); pages 273–5.
16. L. F. Reichle, "Evaluation of All Potential Sources of Energy for Desalting," in *Proceedings of the First International Symposium on Water Desalination*, US Dept. of the Interior (1965); page 605.
17. R. H. Sabersky, Int. J. Heat Transfer **14**, 1927 (1971). □