Solar Energy Utilization by Physical Methods

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An interesting feature of solar energy is that it can be utilized through a multitude of differing methods. Solar energy utilization does not require a great deal of technology development, since technical feasibility has been proved for most approaches, so that the work remaining to be done extends generally to proving or achieving economic feasibility and to applications engineering. Economic feasibility not only includes adequately low cost to facilitate introduction into the marketplace, but also the assurance that the new energy source will become economically significant by being utilized in large scale. This means that it should not only be cost competitive with other internally or externally available energy resources but should be usable in adequate quantity at realistic price, should the old energy sources not be procurable in sufficient quantity at acceptable prices. In this case, the new resource can prevent the general economic development from being stymied, and can exert a stabilizing influence on the economic availability of the other energy sources. Two preliminary conditions to achieving this status, the adequate availability of solar energy in the United States and the potential utilization without significant ecological problems, have been extensively discussed (*1*). The discussion can therefore turn to the state of technological development and, particularly, to the potential for meeting both the economic requirements for quantity and the cost of the various approaches to the utilization of solar energy. The question then becomes one of time scale which may conveniently be broken: (i) the short range with prime emphasis on overcoming ecological and social problems and on local or temporary energy supply shortages (up to 1980); (ii) the medium range, characterized by increasing general shortages of natural gas and petroleum (up to 2000); and (iii) the long range in which these two resources will be essentially exhausted, and, if consumption should have increased as frequently predicted, concern about large-scale thermal pollution may start to mount.

Fig. 1. The seven-story laboratory building at Odeillo, with the parabolic reflector mounted on its north wall and the target building to the right. [Courtesy of *Life*]

The various approaches to solar energy utilization can be divided into four groups: indirect methods using meteorological or geophysical effects; utilization of biological effects; direct use for heating; and conversion to electricity. The approaches, with exception of the second, are discussed in the following sections.

Indirect Utilization of Solar Energy

Hydropower, among the first sources of mechanical energy for man, has also been utilized for the generation of electricity before the introduction of steam power plants. It is efficient (~ 90 percent), economical, and supplies at present approximately 17 percent of the total electricity generated in the United States. Apart from high capital costs, there are ecological reasons for avoiding the construction of numerous further dams. Approximately one-third of the total hydropower potential of the United States is already developed, so that a large increase in hydropower utilization will not be possible.

Wind power has, in the past centuries, been extensively used to provide mechanical energy. Now, however, the wind power plants with their intermittent output have become obsolete through the availability of power on demand from cheap fossil fuels. With the coming shortage in fossil fuels, and the design of larger and more efficient aeroturbines, a new interest in the use of wind power is manifest. A conceptual design with aeroturbines stationed off the Atlantic coast to produce 160 billion kilowatt-hours of electricity a year has been completed for the New England region (*2*). Limiting factors in the large-scale utilization of wind power are a combination of available wind energy and the possibility of weather modification. Thus, according to conservative estimates, 1 percent of the electricity consumption or 0.43 percent of the total energy consumption in the United States could be supplied by wind power in the year 2000 (*3*). This schedule depends on government support for technology de-

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velopment and proof of feasibility, with industry carrying out the development of this resource after feasibility of the approach has been established. It is interesting to note here the recent announcement of a joint NSF-NASA effort to develop a 100-kilowatt wind generator.

Ocean thermal gradient power plants are based on the utilization of vertical temperature profiles which are established in the ocean waters by absorption of sunlight in the upper layers of the ocean, combined with density separation by depth. In certain areas, the resulting temperature gradients are enhanced through the action of ocean currents, such as the Gulf Stream off the East Coast of the United States. Although the temperature differences are relatively small, it is expected that conversion to electrical power can be accomplished with an efficiency that approaches 2 percent. Since this thermal energy is continuously available without fuel cost, and since its utilization creates no thermal pollution if carried out on a moderate scale, the approach looks basically attractive. The temperature difference between the Gulf Stream surface water and that at a depth of 2000 feet ranges from 15° to 22°C. A collection system of units moored at 1 mile spacing along the length and breadth of the Gulf Stream off the coast of Florida is thought to be capable of energy production equal to the total 1970 U.S. energy consumption (*3*). From a conceptual design for such an ocean thermal gradient power plant using low-temperature vapor turbines it has been estimated that such units can produce electric power at competitive cost (*4*). If sufficient support is given to development, it has been estimated that 1 percent of the electricity consumed in the United States in the year 2000 could be provided from ocean temperature differences.

Solar Energy for Heating

Use of solar energy in the form of heat has been made for more than 2000 years. Such heat has been used for the distilling of liquids—for example, of perfume in the ancient and medieval times, and of fresh water, which is now being produced from the seawater surrounding Mediterranean and Caribbean islands; for the drying of materials, particularly agricultural products such as hay, raisins, and lumber; for the heating of water for household consumption—which is very common in Israel and in Japan, and which is also used in Florida; for the heating of houses for which a few experimental units are in operation in the United States; for the experimental operation of absorption refrigeration systems for cold storage as well as air conditioning purposes; for the generation of high-temperature heat by means of optical concentrators, which were used for the ignition of wooden ships in warfare 2100 years ago, as well as for metallurgical purposes for which the largest system ever built is in operation at Odeillo in the French Pyrenees (Fig. 1), producing more than a megawatt of power and reaching temperatures of 3300°C.

These systems for the direct use of heat generated from solar energy operate at high efficiency (~ 50 percent reachable in simple systems), are technologically the best developed of any solar energy utilization systems, and are

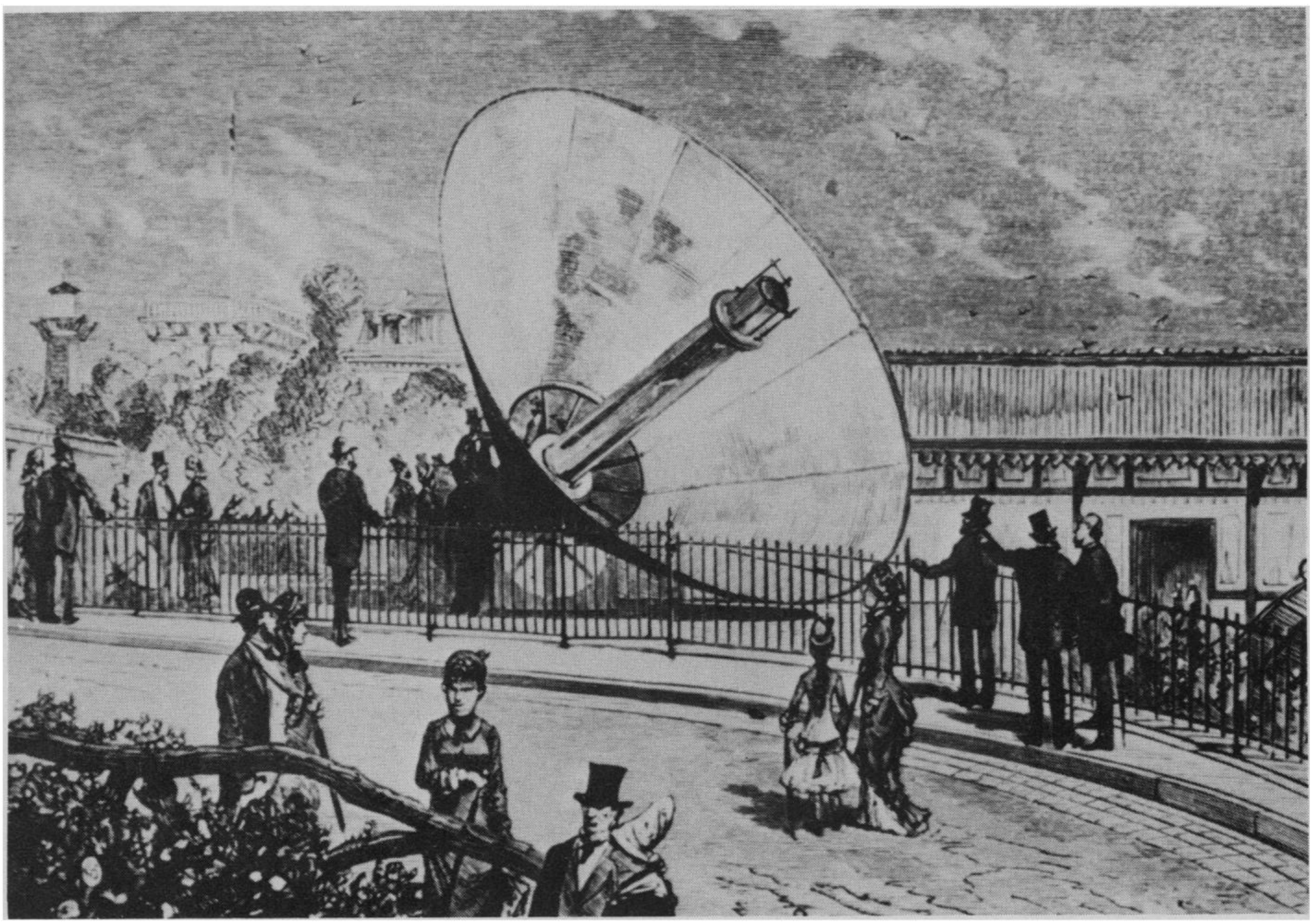
Fig. 2. Solar collector driving steam engine, exhibited by Mouchot at the World's Fair in Paris, 1878.

Table 1. Energy consumption in the United States in 1967 (*11*).

User	Energy used (10^{12} kilowatt-hours)					
	Space heating	Other heating	Electricity*	Motive power	Other	Total
Residential	2.08	0.69	0.87			3.64
Commercial	0.35	0.69	0.52			1.56
Transportation	0.17			3.47		3.64
Industry	0.35	3.47	1.73		0.69	6.24
Other	0.17	1.04	0.52		1.21	2.94
All users	3.12	5.89	3.64	3.47	1.90	18.02

* The figures for electricity are thermal energy input to all utilities.

closest to providing energy competitively to energy from other sources (*5*). They also address an area of greatest use of energy (Table 1). Solar domestic water heaters are available in Florida (*6*), where they provide energy at lower cost than that provided by electric power, and at not more than twice the present costs of gas. These systems are produced in very small quantities, essentially in hand operation, and mass production methods should result in cost reductions to levels where these solar collectors can provide energy competitively with any other source.

A similar approach to that used for domestic water heating can be applied for the heating of houses. Such systems can, if combined with thermal energy storage of a capacity corresponding approximately to 1 day's use, economically produce 50 to 75 percent of the annual energy consumption for heating, cooling, and hot-water preparation in a building (*5*). This figure applies in many parts of the United States, including the highly populated northeast coast. Since the collectors would normally be mounted on walls or roofs of building structures, no additional land area would be required for this source of energy, thus causing no ecological effects beyond those of the building itself. Even visual pollution would be minimal. It has been estimated that these systems would provide, in the year 1985, up to 1 percent of the total energy consumption in buildings, or 0.15 percent of the total national energy consumption, and 10 and 35 percent of the energy consumption in buildings by the years 2000 and 2020, respectively, which would then amount to 1.2 and 3.5 percent of the total national energy consumption (*3*).

The other areas of conversion of solar energy into heat are at present not considered to be of similarly great significance and are therefore not included in the forecast, except for the generation of heat for the conversion to electricity.

Electric Power Generation

For the generation of electric power from solar energy, two basic routes are available: (i) the sequential conversion from sunlight to heat, to steam, to

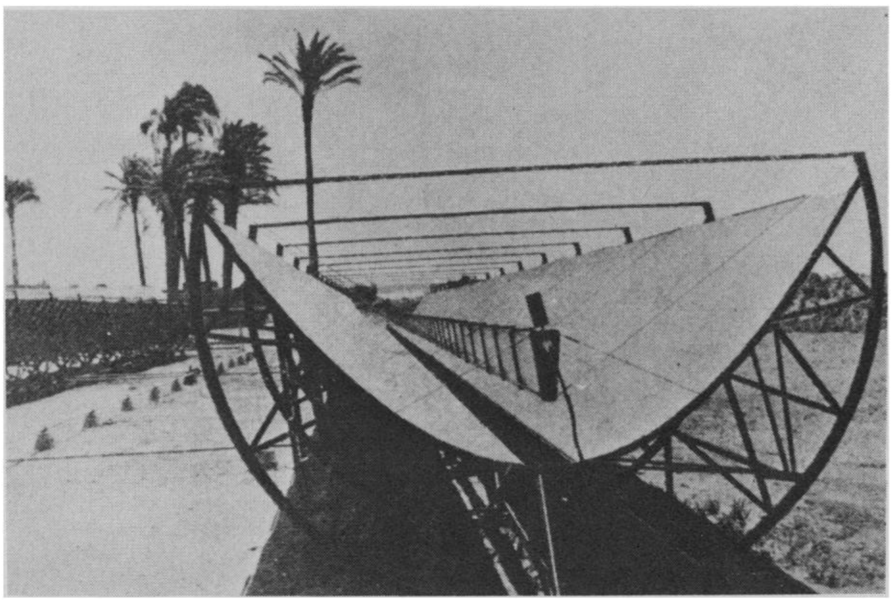

Fig. 3 (above). The "solar power farm" built by the Philadelphia engineers Shuman and Boys in 1912 at Meadi, Egypt, providing steam for a 100-horsepower piston engine (visible in shed at right). Fig. 4 (left). One of the sun-tracking collectors of the Shuman-Boys plant with the boiler tube in the focal line of the cylindrical paraboloid reflector.

mechanical power, and ultimately to electric energy; and (ii) the direct conversion of sunlight to electricity by the photovoltaic process. The first route has been experimented with quite extensively. A working system, where a water pump was driven in lieu of the electric generator, was demonstrated by A. Mouchot at the Paris World's Fair in 1878 (Fig. 2). Also, the Philadelphia engineer F. Shuman built a 100-horsepower (1 metric horsepower is $\sim 7.4 \times 10^2$ watts) solar power steam engine plant in Egypt, 11 kilometers south of Cairo, in 1912 (Figs. 3 and 4). It is interesting to note the similarity of some of the proposed designs for solar plants to that of this early plant. However, the general technology has considerably advanced, and improved materials and methods are now available which can result in significantly higher efficiencies (15 to 20 percent is a reasonable expectation, and 30 percent has occasionally been mentioned) and lower systems costs (*7*). The work remaining to be done will therefore be focused on the application of this new technology to achieve acceptable cost-performance data, to determine the optimum system size and approach, and to prove technical and economic feasibility of large solar power stations. At present, the cost of electric power generated by this approach is predicted to be higher by a factor of 4 than power from fossil or nuclear power plants.

Photovoltaic solar energy conversion by means of silicon solar cells has provided the power for nearly all the spacecraft, launched by any nation, which were designed for missions exceeding 2 to 3 weeks duration. These cells have proved to be a reliable source of power, more suitable for spacecraft than any other. For terrestrial applications, the current price of solar power arrays is much too high to permit consideration of large-scale application (the efficiency is 13 to 14 percent on commercially available units, and is 16 percent on laboratory units). This high price has partially been the result of very small production (50 to 70 kilowatts per year) for a very restricted market, which provided no incentives for the development of very low cost processes. Thus, considerable impovements in process methods, partially also based on materials other than silicon—for instance, cadmium sulfide—will be necessary to permit large-scale terrestrial applications.

An advantage of the photovoltaic system is that its size is not limited and that it therefore can easily be used at the site of energy consumption, potentially matching the distributed nature of sunlight to the distributed pattern of energy consumption. Photovoltaic solar arrays can be mounted on roofs or walls of buildings—eliminating the use of additional land area—and can even be combined with solar collectors that are used for space heating or hot-water preparation, to form a particularly efficient and economical system.

Both approaches to electric power generation, that via heat and the photovoltaic route, basically provide power only during times of incoming solar radiation. To supply energy at all times of demand, they require storage—which can be heat storage for the steam systems, but has to be either electrical, mechanical, or chemical storage for the photovoltaic system.

Provided that government support for technology development and proof of feasibility is available, it has been estimated that 1 percent of the total electricity generation in the nation could be provided by solar energy through either one of the two routes in the year 2000; this would be 0.43 percent of the total energy consumption. In addition, through photovoltaic systems on buildings, 0.45 percent of the total national energy consumption could be provided in the year 2000 (*3*).

An unusually advanced concept to electric power provision utilizes a space station in synchronous orbit, carrying huge arrays (32 square kilometers) for the photovoltaic conversion of solar energy to electricity (*8*). This energy would be beamed by a microwave link to receiving antennas on the ground (10,000 megawatts available on the ground). The approach has the advantage that solar energy can be converted to electricity for 24 hours per day, eliminating the requirement for energy storage. Although this proposal is very ambitious, it seems quite probable that, with little more than the available technology, technical feasibility can be demonstrated. And, assuming the availability of six to ten times more solar energy in synchronous orbit than on the earth's surface. there exists also the potential for economic feasibility. If there is government support for development, which will have to be most substantial in this case, it has been estimated that these space systems could provide 0.43 percent of the total national energy consumption in the year 2000 (*3*).

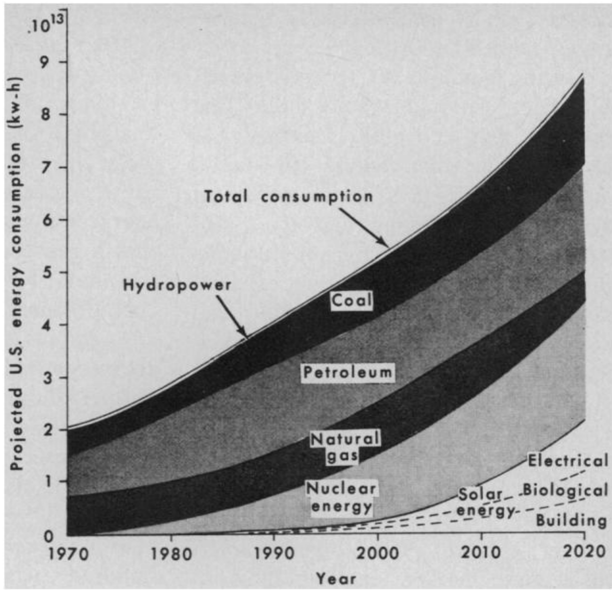

Fig. 5. The potential share of solar energy in the future energy supply, as contributed by the various sources. Data for the nonsolar energy contributions are from (*10*), but are adjusted for solar energy contributions according to the penetration percentages given in (*10*) and distributed over the other energy sources according to energy use and energy source distribution for these uses.

Conclusion

On the basis of the estimated contributions of these differing methods of the utilization of solar energy, their total energy delivery impact on the projected U.S. energy economy (*9*) can be evaluated (Fig. 5). Despite this late energy impact, the actual sales of solar energy utilization equipment will be significant at an early date. Potential sales in photovoltaic arrays alone could exceed $400 million by 1980, in order to meet the projected capacity buildup (*10*). Ultimately, the total energy utilization equipment industry should attain an annual sales volume of several tens of billion dollars in the United States, comparable to that of several other energy related industries.

Varying amounts of technology development are required to assure the technical and economic feasibility of the different solar energy utilization methods. Several of these developments are far enough along that the paths can be analyzed from the present time to the time of demonstration of technical and economic feasibility, and from there to production and marketing readiness. After that point, a period of market introduction will follow, which will differ in duration according to the type of market addressed. It may be noted that the present rush to find relief from the current energy problem, or to be an early leader in entering a new market, can entail shortcuts in sound engineering practice, particularly in the areas of design for durability and easy maintenance, or of proper application engineering. The result can be loss of customer acceptance, as has been experienced in the past with various products, including solar water heaters. Since this could cause considerable delay in achieving the expected total energy impact, it will be important to spend adequate time at this stage for thorough development.

Two other aspects are worth mentioning. The first is concerned with the economic impacts. Upon reflection on this point, one will observe that large-scale solar energy utilization will not cause a greater impact than other new energy sources, based on the reasoning that a self-consistent set of conditions will have to be fulfilled in order to achieve such large-scale use. Without cost competitiveness, other energy resources would fill the requirements, or, if their resource and cost structure also would create severe problems, the economic forecasts simply cannot be fulfilled. We also should not think of a "solar-only" energy future. First, there is still enough coal to last for several hundred years. Second, there should be enough fissionable fuel available to operate breeder reactors for a similar time span, and geothermal energy could satisfy some requirements for a long time. And finally, there may be fusion. It would be unlikely that any one of the available options should play a really dominant role. Rather, we should expect to be using an energy mix, just as we do now, with each energy source supplying the requirements which it can satisfy in the most suitable way, and solar energy should play an important role in this long-range future.

References and Notes

1. A. M. Zarem and D. D. Erway, *Introduction to the Utilization of Solar Energy* (McGraw-Hill, New York, 1963); I. Bennett, *Solar Energy* **9**, 145 (July 1965); G. O. G. Löf, T. A. Duffie, C. D. Smith, *ibid.* **10**, 27 (January 1966); M. Altman, M. Telkes, M. Wolff, *Energy Conver.* **12**, 53 (1972).
2. W. F. Heronemus, private communication.
3. "Solar energy as a national resource," report of the NSF/NASA Solar Energy Panel to the Office of Science and Technology; available from the Department of Mechanical Engineering, University of Maryland, College Park, Maryland.
4. J. H. Anderson and J. H. Anderson, *Mech. Eng.* (April 1966), p. 41; C. Zener, *Phys. Today* (January 1973), p. 48.
5. H. G. Lorsch, *Energy Conver.* **13**, 1 (1973).
6. R. A. Tybout and G. O. G. Löf, *Natl. Resources J.* **10**, 268 (1970).
7. R. C. Jordan, private communication; A. B. Meinel and M. P. Meinel, *Phys. Today* (February 1972), p. 44.
8. P. E. Glaser, Proceedings of the Intersociety Energy Conversion Engineering Conference (SAE), Boston, August 1971, p. 38; private communication.
9. "Reference energy systems and resource data for use in the assessment of energy technologies," *Report AET-8 for the Office of Science and Technology under contract OST-30* (Associated Universities, Upton, N.Y., 1972).
10. M. Wolf, "Cost goals for silicon solar arrays for large scale terrestrial applications," in *Proceedings of the 9th IEEE Photovoltaic Specialists Conference*, 2 to 4 May 1972, Silver Spring, Md. (Energy Conversion).
11. S. F. Singer, *Sci. Am.* **223**, 174 (September 1970).

Science Bibliography of Energy

Certain topics relevant to the subject matter of this issue of *Science* were omitted because they had already been treated in recent issues of the magazine. A list of these articles and the date of publication follows:

Group I: Contributed Articles (Reprints Available)

C. A. Berg, "Energy Conservation through Effective Utilization," **181**, 128 (1973).

G. A. Lincoln, "Energy Conservation," **180**, 155 (1973).

L. A. Sagan, "Human Costs of Nuclear Power," **177**, 487 (1972).

A. W. Eipper, "Pollution Problems, Resource Policy, and the Scientist," **169**, 11 (1970).

A. M. Weinberg, "Social Institutions and Nuclear Energy," **177**, 27 (1972).

D. Chapman, T. Tyrell, and T. Mount, "Electricity Demand Growth and the Energy Crisis," **178**, 703 (1972).

E. Hirst and J. D. Moyers, "Efficiency of Energy Use in the United States," **179**, 1299 (1973).

D. Pimentel, L. E. Hurd, A. C. Bellotti, M. J. Forster, I. N. Oka, O. D. Sholes, and R. J. Whitman, "Food Production and the Energy Crisis," **182**, 443 (1973).

E. F. Osborn, "Coal and the Present Energy Situation," **183**, 477 (1974).

J. O'M. Bockris, "A Hydrogen Economy," **176**, 1323 (1972).

L. W. Jones, "Liquid Hydrogen as a Fuel for the Future," **174**, 367 (1971).

D. F. Othmer and O. A. Roels, "Power, Fresh Water, and Food from Cold, Deep Sea Water," **182**, 121 (1973).

T. B. Reed and R. M. Lerner, "Methanol: A Versatile Fuel for Immediate Use," **182**, 1299 (1973).

W. E. Winsche, K. C. Hoffman, and F. J. Salzano, "Hydrogen: Its Future Role in the Nation's Energy Economy," **180**, 1325 (1973).

Group II: Staff-Written Articles—News and Comment

L. J. Carter, "Deepwater Ports: Issue Mixes Supertankers, Land Policy," **181**, 825 (1973).

"Rio Blanco: Stimulating Gas and Conflict in Colorado," **180**, 844 (1973).

R. Gillette, "Budget: Energy," **183**, 635 (1974).

"Synthetic Fuels: Will Government Lend the Oil Industry a Hand?" **183**, 644 (1974).

"Energy: The Muddle at the Top," **182**, 1319 (1973).

"Western Coal: Does the Debate Follow Irreversible Commitment?" **182**, 456, (1973).

"NAS: Water Scarcity May Limit Use of Western Coal," **181**, 525 (1973).