# ECONOMIC ASPECTS OF UNCONVENTIONAL ENERGY RESOURCES

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The two most important unconventional energy resources today are atomic energy and solar energy. Importance is here judged by the ability of these two energy resources to shoulder important parts of the world's energy load before the end of the present century. It is also influenced by a lack of resource restrictions for the indefinite future in the case of solar energy and a comparative lack of resource restrictions in the case of atomic energy if, as and when the breeding of nuclear fuels becomes economically attractive. But this judgment of high promise in the case of atomic energy remains qualified, as we shall note, by problems of disposing of the large quantities of nuclear waste materials that would be created by extensive nuclear power generation.

The unconventional energy resources abound, but are either inherently limited in possible significance or unproven economically to the best knowledge of the author. In the first group are wind and geothermal energy. For specific locations, geothermal energy has been of considerable value, but current commercial output is even now only about 1,000 megawatts electrical (MW), with about as much again in the form of known reserves.[1] The prospects for utilization of wind power are similarly limited. After careful study, Putnam gives wind power a potential approximately one-fifth that of hydroelectric power in the world's energy economy,[2] which in turn seems destined to supply only one or two per cent of the world's energy load for the foreseeable future.[3] Putnam's analysis was heavily influenced by his requirements for constancy of wind speed, which might not be as important if low cost storage becomes available. In the second category are a variety of devices of unknown potential, including fuel cells, controlled biological photosynthesis of fixed carbon in alga and others. By definition, these are beyond the scope of the present analysis (and its author).

## Nuclear Power

Economic analyses of the prospects for nuclear power have been dominated within the past year by the decision of an electric utility, Jersey Central Power and Light Company, to build a nuclear plant, the Oyster Creek Nuclear Electric Generating Station, to produce electric power at a cost in the range of 4 mills per kilowatt-hour (kwhr).[4] This cost is below that which the Atomic Energy Commission (AEC) had predicted likely by 1970-75 in its 1962 "Report to the President."[5] The turn of events naturally has attracted considerable attention and will be used here as a starting point for appraisal of the economics of nuclear power. The central question pursued in the following paragraphs is whether Jersey Central's calculations reflect the true cost of nuclear electric power today. It will be found that they come close to doing so, but that for a society-wide evaluation of the portend of nuclear power, somewhat higher costs should be used. The latter are supplied and their implications for the further adoption of nuclear technologies suggested.

### Cost Determinants

There are five important economic variables that determine the relative costs of nuclear power and conventional fossil fuel generated power in any given situation. These are:

1. Annual fixed charge on capital
2. Use factor (defined as ratio of kwhr actually generated over plant lifetime to product: plant capacity x lifetime hours in service)
3. Size of plant
4. Level of fuel cost
5. Public policy

The first two variables are important because nuclear power is more capital intensive than conventional power, i.e., for a given level of output, a larger proportion of nuclear power costs are in the form of capital expenses than is the case for conventional power. Thus, a low annual fixed charge and a high use factor both favor nuclear power and the converse of both favor fossil fuel power. The third variable derives its importance from the fact that nuclear power costs are reduced proportionately more by increasing plant size than are conventional power costs. The larger the plant, the more favorable are the per kwhr costs for nuclear power.

The level of fossil fuel cost is influenced in important degree by transportation expenses. Thus, the range in fuel cost in the United States is from 8 cents per million BTU in Texas to over 40 cents per million BTU in parts of New England and the Far West.[6] In contrast, nuclear fuel is for all practical purposes weightless per unit energy content. One pound of nuclear fuel is the equivalent of 1300 tons of coal. To the extent that nuclear power comes into use at competitive cost levels in the United States, it will tend to even out the geographic cost structure of electricity, though improvements in the technology of long distance power transmission are already working in this direction.

Finally, there is the effect of public policies. AEC has helped finance a large number of high cost nuclear power stations as a way of advancing power technologies,[7] and there is every reason to expect these policies will continue. The costs of the plants and the power they produce must be charged against technological progress, including the development of converter and breeder reactors. The same must be said of various public aids to large nuclear plants now on the line but embodying earlier versions of technologies now becoming competitive.[8] To the extent that public costs are incurred for nuclear power stations, these are part of the total costs that must be counted on a social balance sheet for the evaluation of nuclear power.

Oyster Creek Plant

Table 1 summarizes the comparison of fossil fuel and nuclear power costs made by Jersey Central. Three alternatives were considered: (1) a mine-mouth coal-fired plant in western Pennsylvania which would feed electricity into the GPU system[9] through additional high voltage transmission lines; (2) a coal-fired plant at the Oyster Creek site; and (3) the Oyster Creek nuclear plant. All production costs have been reduced to annual equivalents.[10] The figures reported by Jersey Central were for blocks of years by plant age: 1-5 years, 6-10 years, 11-20 years and 21-30 years. Annual costs were different in each block of years, due especially to a variation in expected fuel cycle costs. In reducing the Jersey Central figures to annual equivalents, the reported costs for each block of years were multiplied by their present worth factors and the sum of all such weighted costs were divided by the present worth factor for the entire 30 year period.

The three different capacities listed for the Oyster Creek Nuclear Plant reflect an expected "stretch-out" in capacity after the plant gets into operation. General Electric, the supplier of the nuclear plant, has set a guaranteed capacity of 565 KW but anticipates that "stretch-out" will be realized. Jersey Central plans for the 620 KW "stretch-out", but even with a "stretch-out" to 565 KW, the figures in Table 1 give the edge to the nuclear plant. It is interesting also to note from Table 1 the advantage of the Western Pennsylvania over the Oyster Creek Fossil Fuel plant, attesting to the low costs of long distance power transmission today. As a result, a plant located at the mine mouth can take advantage of the lower costs of shipping electricity rather than coal.

TABLE 1

Jersey Central Power and Light Company
Cost Comparisons for Oyster Creek Plant
(lifetime annual equivalent costs, mills/kwhr)

| | Fossil Fuel Plants (600 MW) | | Oyster Creek Nuclear Plant | | |
|---|---|---|---|---|---|
| | Western Pa. | Oyster Creek | 515MW | 565MW | 620MW |
| Plant cost, $/KW[a] | 105 | 110 | 132 | 120 | 100 |
| Fossil fuel cost per $10^6$ BTU | 17¢ | 26¢ | | | |
| Fixed charges, mills/kwhr[b] | | | | | |
| Plant and other working capital | 1.771 | 1.449 | 1.770 | 1.613 | 1.474 |
| Fuel working capital | 0.033 | 0.047 | 0.348 | 0.326 | 0.294 |
| Fuel expense | 1.599 | 2.301 | 1.384 | 1.371 | 1.365 |
| Other operation and maintenance | 0.493 | 0.405 | 0.594 | 0.551 | 0.516 |
| Total[c] | 3.897 | 4.203 | 4.096 | 3.861 | 3.650 |

[a] Transmission costs are included in fixed plant costs.

[b] Annual equivalent costs are the weighted average of age-related costs reported by Jersey Central. Weighting was made using present worth factors. Jersey Central used a 10.39% fixed charge on capital, straight line depreciation expected life of 30 years in all plants and 40 years on transmission facilities. Lifetime load factors were assumed identical for all plants at 83 percent, but the load factor calculation for the fossil fuel plants was made using an "equivalent system" technique. See Report, pp. 13-14.

[c] Minor differences between totals and sums of corresponding figures are due to rounding.

Source: Jersey Central Power and Light Company, Report on Economic Analysis for Oyster Creek Nuclear Electric Generating Station (February 17, 1964), Tables 1, 2, 3 as modified by footnote b, above.

The relevance of the Jersey Central results for a nation-wide evaluation of nuclear power depends on a number of considerations, including at least three points that have been raised in public discussion: (1) the appropriate annual fixed charge; (2) the prospects for "stretch-out"; and (3) whether the bid price by the General Electric Company for the nuclear portions of the Oyster Creek plant represents true costs to GE (at some assumed volume of production of similar plants), or whether, as some have argued, GE bid too low for the plant costs to be considered typical.[11]

It is unavoidably true that Jersey Central used methods of determining required revenue for fixed charges that reflect rate making practices in the state of New Jersey and the financial structure of the utility itself (although the latter was simplified for the sake of the public report). It is another matter, however, to develop figures for a national comparison. Using average state and federal taxes, average cost of capital and other representative conditions, the Federal Power Commission recommends a figure of 13.9 per cent fixed charge on capital in making comparisons of production costs.[12] For the purpose at hand, this figure will be rounded down to 13.5 per cent to reflect the 1964 federal corporation income tax reduction combined with omission of insurance charges. This is significantly higher than the 10.39 per cent used by Jersey Central. Insurance charges are treated separately since they are very different for the nuclear and conventional plants.

The evidence regarding "stretch-out" is inconclusive. Philip Sporn, a respected spokesman for the electric utility industry, has estimated that ten per cent is the most likely "stretch-out."[13] A General Electric spokesman predicts that the future trend will be toward design and cost estimates with less than 20 per cent stretch.[14] In the absence of more conclusive information, the 10 per cent figure is here judged safest to use for nuclear power cost comparisons.

The General Electric Company is probably the best authority for the question of future contract prices involving the GE boiling water reactor. The prices and policies published by GE on September 21, 1964 form the basis for data that will be used to represent the nuclear power potential in Table 2. The GE costs are slightly higher than those for the Oyster Creek plant, but the difference is not great.

Cost Comparison of Nuclear and Conventional Power

The various refinements indicated above have been incorporated in Table 2 to give a general comparison of nuclear with coal-fired technology in the large central station plants here discussed. Some differences remain in nuclear fuel and other operating expenses; therefore two sets of estimates are given for these. It will be noted that the Sporn and GE estimates (both of which have been modified by the present author, as indicated in Table 2) are in good agreement. Their greatest difference is in cost of insurance. On this point, the Sporn total of insurance plus operation and maintenance costs is closer to that of the Oyster Creek plant than is the corresponding GE total.[15] Coal-fired plants are represented by Mr. Sporn's Cardinal plant technology, the most advanced under construction today.

The most important message conveyed by Table 2 is that nuclear power plants can be built today at a lower cost to electric utilities than the best coal-fired plants in regions of moderate to high fossil fuel cost. Moreover, the progress in nuclear technology that has led to this result is sufficiently impressive to give credence to claims of expected continued downward trends in fuel costs,[16] which will in turn further reduce nuclear fuel operating expenses.

Social Costs

The question immediately arises as to whether all costs of nuclear power are represented in Tables 1 and 2. Insofar as taxes are concerned, no differentiation can be made between nuclear and conventional power since the FPC rate of 13.5 per cent was used for both. There are, however, three AEC policies that help defray costs of nuclear power: (1) design assistance; (2) waiver of fuel use charge for first five years of operation; and (3) price supports for byproduct plutonium production.

TABLE 2

GENERAL COST COMPARISON OF NUCLEAR AND COAL-FIRED PLANT TECHNOLOGIES

(lifetime annual equivalent costs, mills/kwhr)

| | Coal-Fired Unit (Cardinal-type plant) | | | Nuclear Unit (Boiling Water Reactor) | |
|---|---|---|---|---|---|
| Capacity, megawatts | 615 | | | 600 | |
| Unit capital cost, $/KW | 107 | | | 126[a] | |
| | Coal costs per $10^6$ BTU | | | | |
| | 20¢ | 25¢ | 30¢ | Sporn estimates | GE estimates |
| Fixed charges | | | | | |
| Plant[b] | 2.07[b] | 2.07[b] | 2.07[b] | 2.43[b] | 2.43[b] |
| Fuel working capital[c] | 0.03[c] | 0.04[c] | 0.05[c] | 0.33[c] | 0.33[c] |
| Fuel expense | 1.73 | 2.16 | 2.60 | 1.45[d] | 1.51[e] |
| Operation and maintenance | 0.30 | 0.30 | 0.30 | 0.35 | 0.31 |
| Insurance | neg.[f] | neg.[f] | neg.[f] | 0.20 | 0.08 |
| Total | 4.13 | 4.57 | 5.02 | 4.76 | 4.66 |

[a] Estimated plant costs at $121. per installed kilowatt by interpolation of informa-formation supplied by GE, increased by 15 percent to allow for construction, interest, land and related cost as in Stathakis (see source of this table) to give $139. per kilowatt, which was divided by 1.10 to allow for ten percent stretch-out, giving the resulting $126. per kilowatt.

[b] Based on 13.5 percent fixed charge, 80 percent load factor.

[c] Obtained from Table 1 supra. Fuel working capital costs were omitted in all original estimates. It will be noted that the fuel working capital costs used in Table 2 were based on fixed charges of 10.39 percent as opposed to 13.5 percent used in the remainder of this table. No correction has been made for this difference because of the complexities of imputing fuel costs at different periods of time. The understatement in turn aids nuclear power more than conventional power.

[d] Equivalent annual fuel expense obtained by Sporn apparently using weighted average lifetime value obtained by present worth factors.

[e] For representative "equilibrium core" as described by Strathakis (see source of this table).

[f] Insurance on conventional plants is calculated using the Federal Power Commission recommended rate of 0.25 percent for each kilowatt of capacity investment.

Source: Coal-fired unit and Sporn estimates of nuclear unit are from Philip Sporn, "A Post-Oyster Creek Evaluation of the Current Status of Nuclear Electric Generation", Joint Committee on Atomic Energy, 88th Congress, 2nd Session, Nuclear Power Economics - Analysis and Comments - 1964,(Washington, D.C., 1964), Table 4 except as modified by footnotes above.

GE estimates are from G. J.Strathakis, "Nuclear Power Drives Energy Costs Down", Electrical World (October 5, 1964) except as modified by footnotes above.

These three are available for large central stations of the type here under discussion.

Design costs may or may not be large, depending on whether research and development is necessary for any parts of the system. If so, AEC is willing to finance the research and development costs[17] and this part of the expense must be regarded as a subsidy in the interest of progress, as noted in previous discussion. The Oyster Creek plant was not designed at AEC expense, nor did it utilize design concepts that necessitated R&D programs. Hence the figures shown in Table 1 include design expenses, but for a plant whose basic technology had been previously established. Table 2 is based on the same nuclear technology.

The waiver of fuel use charge does not greatly affect the previous calculations. The use charge represents interest on fuel inventory owned by AEC but used by the electric utility. With present AEC policies, Jersey Central estimated that the use charge adds $11 to $13 per kilowatt to the cost of the Oyster Creek plant. Jersey Central did not take advantage of the waiver in its calculations, but if it had done so, the effect would have been to reduce lifetime annual equivalent costs by about 0.06 mills/kwhr in the 10 per cent "stretch-out" (565 KW) plant. AEC has now recommended that legal requirements be changed to permit private ownership of special nuclear materials.[18] Jersey Central calculates that private ownership of fissionable fuels would in its case result in a capital expense of $22 to $30 per kilowatt. The calculations for the Oyster Creek plant assume that private ownership of nuclear fuels will, in fact, commence on July 1, 1973 and the fuel working capital cost reflects this assumption. If private ownership were to exist from the time of initial operation of the Oyster Creek plant, the costs would be about 0.04 mills/kwhr higher for the 10 per cent "stretch-out" (565 KW) plant.[19] Again, the effect of public policy is small enough that no important changes need be made in preceding conclusions.

With respect to plutonium buy-back, AEC has estimated that its current price of $10.00 per gram for plutonium isotopes 239 and 241 in nitrate form represents what the free market price will be in the near future,[20] i.e., before breeder reactors are in commercial use. Insofar as power applications are concerned, this is the economically correct objective and the author is in no position to question the numerical value set by AEC.[21] Jersey Central states that in its calculations, "the total plutonium credit averages less than 0.25 mills/kwhr." Thus, it would take a considerable change in the plutonium buy-back price to affect the competitive status of nuclear power and any future change is more likely to be upward than downward (because of the future possibility of using plutonium reactors for power), which will reduce the cost of nuclear power in today's reactors.

Finally, there is the possibility of social costs in the form of radioactive wastes. These costs are different from any thus far considered in that they will never be encountered in the market place except to the extent that public regulations require methods of radioactive control for which private firms must pay. The prospects for safe waste disposal are not reassuring when account is taken of the large volume of wastes that would be produced by widespread installation of nuclear power. AEC discussed methods of safe disposal in its 1962 "Report to the President" with the clear inference that environmental investigations had not yet reached the point at which reasonable technical criteria had been established for safe disposal of very low radioactive effluents into the environment.[22] AEC also discussed the disposal of high level wastes in its 1962 "Report to the President" indicating in that discussion that "aside from the central reactor development program proper, no other phase of the entire (civilian reactor) program is more important than that of waste disposal."[23] At the same time, AEC indicated that plans for ultimate high level waste disposal were still in the research stage.[24]

Until a safe program is designed to handle ultimate storage of high level wastes in large volume and until environmental standards are established which will prevent undue environmental concentrations of radioactive materials, the author cannot look with equanimity on the expansion of nuclear power generating capacity. If the costs of radioactivity controls increase the costs of nuclear power, then this is as it should be. Those who pay for the power must also pay for the control of any unwanted byproducts. We as a nation have an unenviable history of pollution control. Now, we are talking about pollutants that last decades, centuries in some cases. It is asking very little to decide how we shall live with the volume of radioactive waste materials in prospect before we set out on a course that presupposes their creation.

System Costs

On the assumption that nuclear power costs are fully established to include all social costs of power production, certain observations can be made on the integration of nuclear power in conventional electrical grids.

First, it will be recalled that the data in Tables 1 and 2 are for 600 MW plants. These are large central station plants. At one-tenth the size of the nuclear plant on which Table 2 is based, Strathakis reports over 2 times the cost he estimates for the Table 2 plant.[25] In contrast, Barzel gives results for conventional steam plants which indicate a 48 per cent increase in per kwhr costs as a result of a tenfold reduction in plant size.[26] The inference is that there is a size threshhold above which nuclear power has the cost advantage and below which conventional power has the cost advantage. The size of electric power generating stations depends on a compromise between market density and costs of transmission, to name only the most important variables.[27]

Just as there is a size distribution, so is there a use factor distribution among electric power stations. It will be recalled that high lifetime use factors were employed in Tables 1 and 2 (83 per cent and 80 per cent, respectively). As previously noted, high use factors favor the capital-intensive technology by spreading fixed costs over a larger output. The typical distribution of use factors among electric power stations in a given system is a compromise between age distribution of plants and their operating expenses in the light of the costs of power transmission. Operating expenses are typically highest in the oldest plants; so as plant age increases, it is customary to use the plant a smaller proportion of the time. At the extreme are peaking plants designed for very low load factors using technologies that are least capital intensive and most fuel intensive.

Now, the nuclear power plants that are installed first in any given system can truly be expected to have the highest use factors over their lifetimes. The reason is that they will have lower operating expenses for the same total cost of power than will the conventional plants. Thus, Jersey Central actually expects to realize an 83 per cent use factor with its Oyster Creek plant, but would only expect use factors in the range of 60 per cent with the fossil fuel alternatives[28] (although they were compared at the 83 per cent level). Later calculations for the introduction of nuclear power in the same system, however, will eventually run into more adverse lifetime use factors. There is only so much base load that can be carried in any given system. It is electric power demand that determines the total system output requirements. Eventually, prospective nuclear power additions will be considered in competition with less capital intensive technologies and for lower use factors. Just as there is a need for peaking plants today, so will there be a need for less capital intensive technologies among power plants in the systems of tomorrow.

An approximate indication of the prospects for introducing nuclear energy in today's electric power systems can be found by noting the incidence of large plants in the high and moderate cost fossil fuel areas. The geographic incidence of capacity by fossil fuel cost areas is shown in Table 3 and by plant size in Table 4. Referring to Table 3, it appears that about half of the nation's thermal generating capacity is in the cost range in which an advantage is shown for nuclear power at the 600 MW size level (compare Table 2) if we ignore possible cost differences that might result from different environmental health standards. From Table 4, we note that the number of power plants of large size is relatively limited. There is a tendency, however, for large plant size to be more important in the first, second and eighth FPC regions,

TABLE 3

THOUSANDS OF ELECTRICAL MEGAWATTS OF INSTALLED CAPACITY, 1960

| FPC region[a] | Hydro | Fossil fuel | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Cents per million BTU | | | | | | Total[b] | Average fuel cost, cents per million BTU | |
| | | Below 20 | 20 to 25 | 25 to 30 | 30 to 35 | 35 to 40 | 40 and over | | 1960 actual | 1970 estimated[c] |
| I | 3.9 | 0.9 | 0.9 | 0.5 | 9.7 | 13.0 | 0.1 | 25.1 | 33.6 | 35 |
| II | 0.6 | 8.4 | 8.3 | 6.0 | 5.6 | 0.0 | | 28.3 | 22.8 | 24 |
| III | 6.6 | 4.4 | 5.7 | 6.6 | 3.6 | 1.4 | | 21.8 | 24.8 | 28 |
| IV | 1.1 | 1.3 | 4.3 | 7.0 | 2.6 | 0.8 | | 16.0 | 26.2 | 27 |
| V | 1.1 | 11.9 | 3.1 | 1.0 | 0.1 | | | 16.0 | 17.5 | 20 |
| VI | 1.5 | 0.2 | 0.8 | 0.2 | 0.1 | 0.1 | | 1.4 | 23.8 | 24 |
| VII | 12.2 | | 0.4 | 0.0 | 0.1 | | | 0.5 | 23.4 | 19 |
| VIII | 5.5 | | | | 9.4 | 0.5 | 0.1 | 9.9 | 33.0 | 32 |
| Total[b] | 32.4 | 27.0 | 23.5 | 21.4 | 31.2 | 15.9 | 0.2 | 119.1 | 26.1 | |

[a] For an approximate geographic distribution of FPC regions, see state listings in Table 4, supra.

[b] Totals may differ slightly from the sum of numbers totaled because of rounding.

[c] Estimated costs for 1970 constructed by Edison Electric Institute.

Source: "Cooperative Power Reactor Demonstration Program, 1963", Hearings before the Subcommittee on Legislation of the Joint Committee on Atomic Energy, 88th Congress, 1st Session (July 9, August 7 and October 15, 1963), pp.23 and 24.

TABLE 4

FREQUENCY DISTRIBUTION OF STEAM-ELECTRIC PLANT SIZE, BY APPROXIMATE FEDERAL POWER COMMISSION REGIONS[a]

| | I | II | III | IV | V | VI | VII | VIII |
|---|---|---|---|---|---|---|---|---|
| Plant Capacity MW[b] | Connecticutt<br>Delaware<br>District of Columbia<br>Maine<br>Maryland<br>Massachusetts<br>New Hampshire<br>New Jersey<br>New York<br>Pennsylvania<br>Rhode Island<br>Vermont | Indiana<br>Kentucky<br>Michigan<br>Ohio<br>W. Virginia | Alabama<br>Florida<br>Georgia<br>N. Carolina<br>S. Carolina<br>Tennessee<br>Virginia | Illinois<br>Iowa<br>Minnesota<br>Missouri<br>Wisconsin | Arkansas<br>Kansas<br>Louisiana<br>Mississippi<br>New Mexico<br>Oklahoma<br>Texas | Colorado<br>Nebraska<br>N. Dakota<br>S. Dakota<br>Wyoming | Idaho<br>Montana<br>Oregon<br>Utah<br>Washington | Arizona<br>California<br>Nevada |
| 0 - 10 | 18 | 8 | 1 | 20 | 15 | 19 | 8 | 4 |
| 10 - 25 | 20 | 6 | 1 | 29 | 11 | 14 | 4 | 1 |
| 25 - 60 | 18 | 8 | 8 | 13 | 17 | 2 | 2 | 2 |
| 60 - 100 | 14 | 8 | 7 | 12 | 22 | 2 | 6 | 6 |
| 100 - 200 | 38 | 11 | 15 | 18 | 29 | 2 | 3 | 8 |
| 200 - 300 | 21 | 14 | 12 | 15 | 15 | 1 | 0 | 5 |
| 300 - 400 | 20 | 9 | 7 | 8 | 17 | 0 | 0 | 4 |
| 400 - 500 | 8 | 9 | 8 | 4 | 2 | 1 | 0 | 2 |
| 500 - 750 | 13 | 16 | 4 | 6 | 2 | 0 | 0 | 4 |
| 750 -1000 | 4 | 5 | 0 | 1 | 1 | 0 | 0 | 2 |
| 1000 & over | 1 | 4 | 2 | 1 | 0 | 0 | 0 | 1 |

[a] States have been classified in FPC regions in which the largest proportion of their populations reside in those cases where FPC region boundary cuts through a state.

[b] Lower limit of each capacity range is to be interpreted as having capacities above the indicated levels. Thus a plant of 10.000 MW capacity belongs in the first group; a plant of 10.001 capacity, in the second.

Source: Tabulated from Federal Power Commission, Statistics of Electric Utilities in the United States, Privately Owned, (1962) Section VII.

where fossil fuel costs are higher (compare Table 3). It is clear that the existing geographic structure of conventional fuel costs and size structure of existing power systems permit considerable scope for introduction of nuclear power plants. A more exact conclusion would require considerably deeper analysis, including size and cost trends for both nuclear and conventional plants, which depend not only on plant technological developments, but also on regional fuel cost changes (see last column of Table 3), density of markets for future power, trends in transmission costs and others.[29]

Locational and Aggregative Economic Effects

The effects of reduced electric power costs on different industries in the United States were intensively studied by Schurr and Marschak over a decade ago.[30] Their work is still relevant for this special topic. The lower level of power costs considered in the Schurr-Marschak analysis was 4.0 mills/kwhr, a value which appears from Table 2 within the range of coal fired as well as nuclear powered plants, but the former only for certain regions, not for the broad range of localities where nuclear power might be available.

It would be impossible in a summary to do justice to Schurr and Marschak's findings; moreover, there is the possibility that new process technologies in the industries analyzed could cause some amendments of the details. It is informative, however, to note the three classes of economic effects considered in their study: (1) cost reduction in heavy energy consuming industries, assuming no important changes in process technologies; (2) cost reductions and changes in process technologies that might result from lower energy costs; (3) possible changes in the location of manufacturing establishments as a result of lower cost energy. Only a limited number of industries consumed, or offered sufficient prospects of consuming, enough energy (in proportion to all other costs) to be considered in the analysis. These were: aluminum; chlorine and caustic soda; phosphate fertilizers; cement; brick; flat glass; iron and steel; and rail transportation. Some of these showed sensitivity to energy cost changes if carried to the 4.0 mills/kwhr level. Others did not. We can generalize to the extent of noting that in individual cases and where no process shift was involved, the production of a commodity having ubiquitous inputs or a commodity with no important weight losses between inputs and outputs might become market oriented as the result of lower power costs in the vicinity of consumption centers. The opposite possibility exists where reduced power costs at raw materials centers would attract production operations of a weight losing commodity. In both cases, the availability of low cost nuclear power (or heat) over wide geographic areas must be combined with sufficiently important potential advantages of market, raw materials or other influence to change the balance away from a location that is now strongly affected by low cost power from hydroelectric sites or perhaps from natural gas. Where a process shift is involved, the logic of the situation suggests that bulk energy consumption is entering production processes for the first time and the location of the site of production is reoptimized anew taking account of energy costs in greater measure than before.

The aggregative effects of reduced energy costs on the national economy will be quite small as compared with the total of all other economic activities. AEC estimated in its 1962 "Report to the President" that by the end of the twentieth century, projected uses of nuclear power would result in cumulated savings in generation costs of about $30 billion, the discounted present value of which would be $10 billion at 5 per cent interest.[31] The estimate was based on a simple subtraction of expected nuclear power costs from expected conventional power costs using AEC's projected schedule of nuclear power additions. In comparison with an annual rate of Gross National Product close to $625 billion in 1965 and a projected GNP of $2007 billion in year 2000,[32] the cumulative total in savings do not appear large. But other aggregative effects must be considered.

With a reduction in the price of energy, consumers gain purchasing power, some of which will normally be used for the purchase of additional energy and the rest of which will be used for other purposes. Over a long enough period of time, increases in real income can result in more leisure. All increases in consumption have their secondary and tertiary effects on the suppliers of the goods that are being brought into service, with the result that the effects are perpetuated in infinite regression. It is the total cumulation of all secondary and higher order effects with the initial cost savings that produces a more comprehensive measure of a given real cost reduction. In any particular case, the total effect of the infinite series of derived effects will be to increase the initial benefit (as, e.g., estimated by AEC) several fold, probably by a factor greater than 1.5 and less than 6.0.[33] It is still clear that the aggregative effects of the cost savings will be small as compared with the cumulated Gross National Product for the same years.

Other Uses of Nuclear Power

One possible use of heat from nuclear reactors is for central district urban space heating. This application is similar to the generation of electric power except that steam heat is distributed directly to the consumer location. Space heating consumes 20 per cent of the total energy in the United States today,[34] but at the present time the heat losses from steam distributed by central district plants, combined with the required economies of scale for nuclear power plants, limit prospective applications to densely populated areas where cold winters are experienced. Schurr and Marschak in their exploratory study found that the combination of conditions that might make central district space heating economically attractive are most likely to be found in New York, Boston, Buffalo, Chicago, Milwaukee and Newark, Patterson and Jersey City.[35] The principal difficulty is in the siting requirements. To make such applications economically viable, the nuclear reactor must be located in the middle of a densely populated area. We are not yet ready to approve such location from the standpoint of public safety.

Another closely related application is the generation of nuclear power for the propulsion of ocean vessels. The nuclear ship Savannah immediately comes to mind, but the author is informed that costs on this vessel are unrepresentative of current nuclear propulsion technologies. An approach to the question of costs can be made, however, by noting that the U. S. Navy uses a factor of 1.5 as a rule of thumb in relating nuclear power plant construction costs to those of conventional power plants of the same size for surface vessels.[36] Operating costs are higher, but the extent is not clear from information available.[37] For smaller power plants, such as used in aircraft, locomotives and automobiles, nuclear propulsion seems out of the question for the indefinite future (unless for military purposes, where cost is not a deterrent). If nuclear power is used in the private sector, it will probably be in the form of electrical energy supplied from a central power station.

A step further removed is the direct use of nuclear heat for industrial processes. This topic was the subject of extensive investigation by AEC in the late 1950's. Two difficulties were encountered. First, reactor technologies that are low cost today produce heat at relatively low temperatures as compared with the needs in many industrial processes. Second, before low cost energy can be obtained from a nuclear reactor, it must be of enormous size. As a result of these limitations in combination, "no potentially economic process heat application was found."[38]

A new energy consumer, as yet unimportant in the national (or world) energy economy, is desalinization of water. As population grows and (in the United States, at least) water consumption per capita increases, it is prudent to look ahead to increased needs for fresh water for all purposes. Nuclear power offers some promise as an energy source for distillation. Conventional energy plants in the United States have been built in the range of a million gallons per day to produce water at a cost of about $1.00 per thousand gallons.[39] This is about twice the acceptable cost of municipal water in many parts of the United States, about four times the cost of industrial water and seven or eight times that which is acceptable for most agricultural uses.[40] If plant output is increased approximately a thousand fold to a billion gallons per day, numerous nuclear plant designs suggest that fresh water can be produced from nuclear reactors at costs well within the range of municipal and commercial prices today.[41] With combined fresh water and nuclear electric power production (electric power in the range of 600 to 1200 MW), some of the costs could be borne by electric power sales (assuming large power markets could be reached) and distilled water might be sold at a price low enough to reach the upper range of prices now acceptable for irrigation.[42] The prospect would seem to be of even greater significance to those interested in water rather than energy resources, but the fact that it is based on design, not experience, must be kept in mind.

## Solar Energy

The attraction of solar energy is in its abundance and, from our standpoint, unlimited availability over time. Solar energy reaching Continental United States annually is about $14,700 \times 10^{12}$ kwhr; that reaching the land areas of the world, $246,000 \times 10^{12}$ kwhr.[43] Compare projected energy needs by Schurr et. al. for the United States in 1975 at $21.8 \times 10^{12}$ kwhr.[44] This figure corresponds to the upper limit of a range of energy consumption estimates for the same year made by the present author and extended to an energy consumption upper limit of $52.1 \times 10^{12}$ kwhr in year 2000.[45] If only a fraction of one per cent of the solar energy reaching Continental United States could be usefully employed, it would satisfy all of our energy needs as far in the future as we can predict them.

Solar energy is like nuclear energy in that fuel transportation costs are of no significance. The solar climate varies with the latitude and season of the year but is adequate for many applications over large areas of the world between the forty-fifth parallels north and south. Solar equipment is also like nuclear equipment in that it is capital intensive. The initial investment constitutes a large fraction of total lifetime expense for solar devices. In several other respects, solar energy has economic characteristics opposite those of nuclear power.

Differences in quality are readily apparent. For nuclear power, Roddis cites evidence of load following characteristics and reliability that surpasses even those of the best fossil-fueled plants.[46] Solar energy, on the other hand, is of very low quality due to its low intensity and interruptibility. Low intensity limits the temperatures at which solar energy can be used except where optical focussing systems are employed. For a sufficient expenditure on a solar focussing collector, almost any temperature attainable on earth can be achieved. Interruptibility likewise has its costs, depending on the use envisaged. Energy storage can bridge the nocturnal disappearance of the energy source or can extend collected energy availability over longer periods of time. Energy storage has its costs, but is not always necessary. Low quality interruptible energy might be quite satisfactory in some uses, depending on the design of the prime mover. The interruptibility of solar energy does not prevent its use in certain applications such as water pumping for irrigation. Indeed, there is a rough correlation between the availability of solar energy and the need for irrigation water. The correlation is better for space cooling but tends to be roughly inverse for space heating. Practically continuous energy must be available for still other uses such as food refrigeration and manufacturing. Energy storage costs assume different importance for different applications and will, of course, vary with the solar climate.

Solar energy is also opposite of nuclear power in its scale (or size) economies. Nuclear power tends to find its comparative advantage in mammoth applications, as we have noted. Solar devices are comparatively better in midget applications. Typical of the latter are roof hot water heaters, small scale distillation and, in recent years, midget power units for earth satellites. Solar space heating remains largely in the technological future, but when it comes, it will be best suited for isolated locations where conventional fuels are expensive. In contrast, we have noted that nuclear energy might be used for central district space heat, but only in exceedingly dense population centers. Other examples will become apparent in the course of succeeding analysis.

The solar equipment discussed herein will be for power (terrestial applications), space heat, and water distillation. There are, of course, other applications of solar energy: for cooking, for agricultural drying, for high temperature production in a solar furnace, to name a few. Solar power is potentially important in economic development. Solar space heat offers promise of some day carrying a significant fraction of the space heat load. Solar distillation is important from a long-term water resource standpoint. But all are presently limited by cost considerations. The prospects are sufficiently encouraging, however, to justify an analysis of solar energy's current status.

The solar energy systems will be evaluated using a fixed radiation intensity of 180 Kcal/cm.$^2$,yr. This is a high level of radiation, found in Southwestern United States, North Africa, the Near East, Central India and other locations favorably situated for solar energy.[47] Solar radiation is not the only climatological variable that affects the performance of solar equipment. Two others important in determining heat losses are ambient temperature and wind speed. A comprehensive analysis would take account of the last two, but the results would be oriented more specifically to a fixed location.[48] For present purposes, it will be sufficient to use fixed overall energy conversion efficiency factors. The use of such factors relies on a mean representative effect of other climatological variables, as noted above, and also constitutes an oversimplification in the sense that conversion is typically a nonlinear function of energy intensity. The fixed overall energy intensity being used is, in truth, the average of a yearly pattern that shows considerable variation on a daily and on an hourly basis.

A second difficulty with the use of a single yearly average radiation is that energy storage needs depend on the frequency distribution of radiation intensity. The duration of cloudy weather on any one day must be considered as part of a pattern in which preceding cloudy or sunny days have predetermined the energy that will be in storage at the beginning of that day. Thus, it is necessary to consider patterns of radiation described in a complicated statistical manner or to evaluate equipment performance for a specific identified period (e.g., a year) of weather observations. For the latter purpose, a recursive system such as shown in Figure 1 is required. This system is being used by the author for computer evaluation of solar equipment.

The use function of output energy is equally important. A use function that requires energy during daylight hours only will need less storage than one intended to supply electricity for night lighting. For the sake of equipment evaluation herein, the problems created by the frequency distribution of sunlight and by the use function will not be explicitly resolved. Instead, equipment will be evaluated with different assumed requirements for storage expressed as number of days capacity at the assumed solar radiation intensity level of 140 Kcal/cm.$^2$, yr. In practical applications of solar power units, cases will undoubtedly be encountered in which it is not desirable to attempt to provide sufficient storage, whatever the use function. Such a case is found where the yearly weather pattern regularly brings extended cloudy periods, as in the monsoon climates. In such instances, standby conventional equipment will have to be provided if a solar energy source is to be used at all, or, it might be necessary to employ an alternative use function, depending on the value of energy input for the case at hand. A third possibility is to integrate a wind power system in parallel with a solar power system. In many cases, this approach offers some promise of reducing storage needs. The exact advantages, if any, depend on a comparison of costs of wind power and storage for a given output.[49]

The two principal components of most solar devices are the collector and the storage unit. Where a high temperature heat source is required, as in most power systems, a focussing collector is used. This in turn requires that direct sunlight (direct radiation) be available. Other collectors, such as used for space heating, are nonfocussing and can collect energy in the form of diffuse radiation on cloudy days. Diffuse radiation accounts for about 15 per cent of the radiant energy on clear days. On cloudy days, diffuse radiation may actually increase in absolute value if sky cover is thin or may decrease (in absolute value) if sky cover is heavy.[50]

Economic optimization of equipment design is achieved in any given climate by balancing the cost of collector against the cost of storage for a given energy output with a given level of reliability. Refer to Figure 1. Thus, a given level of $\phi$, say 99 per cent, can be achieved either by increasing the size of the collector or by increasing the capacity of storage. When the size of collector is increased, more energy is collected during sunny days and storage is kept to a level close to its capacity. At the same time, more energy is lost through storage overflow, $\gamma_m$. When the capacity of storage is increased for the same collector size, more is stored, less is collected and less is lost through storage overflow.

In existing equipment, collector expense is typically higher than storage expense. This means that optimization usually requires an expansion of expenditure on storage. The optimum is achieved when the marginal expenditure on collector and the marginal expenditure on storage both yield the same incremental gain in output at the given $\phi$ level. Needless to say, it will not be possible to carry out such optimization with the simplified approach used herein. The $\phi$ reliability of equipment cannot be specified at the present time (or in absence of a more specific climate description and use function) and hence we can hope only to cover the probable range of costs. One might think of increased system costs for the same average output as expenditures for the sake of higher quality energy.

Solar Power Systems

Three types of solar power systems will be considered: (1) thermoelectric; (2) thermodynamic (Tabor); and (3) solar pond. Cost estimates for the three are shown in Table 5. The technologies are in various states of development and cost estimates are by no means as firm as they were for nuclear electric power. Annual equivalent capital costs are calculated at 6 per cent interest with sinking fund depreciation. No tax burden is imputed to the solar equipment in recognition of differences in tax structures throughout the world. It will be noted that fixed kilowatt capacity is rated at an energy intensity considerably above the yearly average, though, of course, the kilowatt-hour output is based on the yearly average.

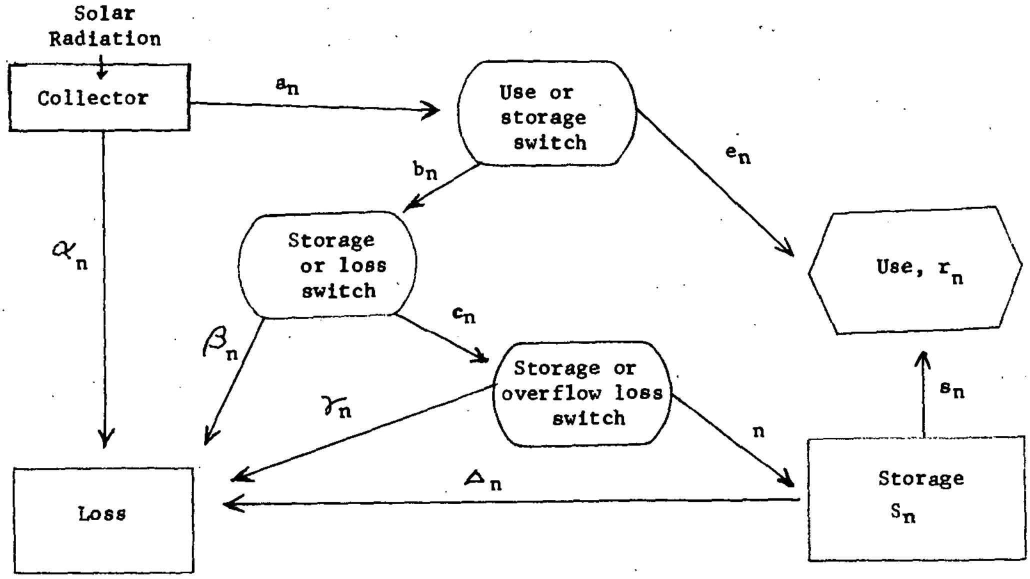
The thermoelectric and thermodynamic systems are focussing systems and hence use only direct normal radiation. The thermoelectric system uses a paraboloid reflector which is continuously adjusted so as to remain normal to the solar beam at all times. The Tabor unit achieves energy concentration by focussing direct radiation in long cylindrical reflectors that are adjusted on an east-west axis in such a way as to set the aperture of the cylindrical reflectors approximately normal to the sun's rays at solar noon. The solar pond is a nonfocussing device that uses all radiation (direct plus diffuse) on a horizontal surface. In making the calculations for Table 5, direct radiation was separated from diffuse radiation using methods described in the reference cited by footnote 50, above.

The thermoelectric system consists of an 8-foot diameter paraboloid collector focussed on a thermocouple cluster. The load and a lead-acid storage battery are connected in such a way as to achieve maximum electric power output. An overall energy conversion factor of 4 per cent is used to take account of all energy losses (optical, thermal and electrical). Representative costs are reported, based on a questionnaire survey of manufacturers of thermocouples, adapted from earth satellite power applications. Since the costs are representative, no single physical thermocouple is envisaged. In the questionnaires, respondents were asked to estimate costs on two bases: (1) costs of existing devices, often built for experimental purposes; and (2) costs of similar devices as they might exist with volume production. Costs in the latter category are used for the thermoelectric system.

The Tabor unit focusses energy on tubes in which vapor is heated to drive a highly efficient small turbine designed for the system.[51] Energy is stored by a phase transformation at about $150^{\circ}$ C, but other information about storage is not available. A full scale pilot unit of the system has been constructed. The costs have been estimated by Dr. Tabor for production of parts using the technology of the experimental unit.

FIGURE 1

SOLAR ENERGY FLOW DIAGRAM




Notation:

| | |
|---|---|
| $a_n$, $b_n$, $c_n$, $d_n$, $d_n$, $s_n$ | energy flows net of losses in time period n |
| $\alpha_n$, $\beta_n$, $\gamma_n$, $\Delta_n$ | energy losses in time period n |
| $r_n$ | energy needed for use in time period n |
| $S_n$ | total energy in storage at the end of time period n |
| K | capacity of storage |

Identities:
1. Radiation received in time period n = $a_n + \alpha_n$
2. $a_n = b_n + e_n$
3. $b_n = c_n + \beta_n$
4. $c_n = d_n + \gamma_n$

Functional relationships:
5. $\alpha_n = f_1$ (radiation received in n, other climatological parameters in time period n)
6. $\beta_n = f_2$ ($b_n$, transfer of energy parameters)
7. $\Delta_n = f_3$ ($S_{n-1}$, storage parameters)

8. $$e_n = \begin{cases} r_n & \text{if} \quad a_n \geq r_n \\ a_n & \text{if} \quad 0 \leq a_n \leq \quad n \end{cases}$$

9. $$d_n = \begin{cases} c_n & \text{if} \quad K-S_n \geq c_n \\ K-S_n & \text{if} \quad K-S_n \leq c_n \end{cases}$$

10. $$s_n = \begin{cases} r_n-e_n & \text{if} \quad S_n \geq r_n-e_n \\ S_n & \text{if} \quad 0 \leq S_n \leq r_n-e_n \end{cases}$$

FIGURE 1 (continued)

Note: 1. All use occurs at the end of a time period
2. Priority of use is $e_n$, then $s_n$
3. All energy is put in storage at the end of a time period

Initial conditions:

$S_o$ = amount in storage at time 0

$S = S_o + d_n - \Delta_n - s_n$

Performance measurement:

$$\text{Let } \phi_n = \begin{cases} 1 & \text{if } e_n + s_n = r_n \\ 0 & \text{if } e_n + s_n < r_n \end{cases}$$

Then $\phi = \sum_n \phi_n$ is the number of time periods sufficient energy was available

Source: The author is indebted to Professor Jesse Shapiro for this conceptualization.

TABLE 5

ESTIMATED SOLAR POWER COSTS

(180 Kcal/cm$^2$,yr. global radiation on a horizontal surface = 194.5 kwhr/ft$^2$,yr. global radiation on a horizontal surface)

| | Thermoelectric unit | Thermodynamic (Tabor) unit | Solar Pond (based on design only) |
|---|---|---|---|
| Available radiation, kwhr/ft$^2$,yr. | 238 direct normal | 185 direct, with adjustment around east-west axis | 194.5 global on horizontal surface |
| Size, KW[a] | 0.175[d] | 4.64 | 14,000/km$^2$ [g] |
| Output, kwhr/yr. | 481.[d] | 10,070.[e] | 31.5 X $10^6$/km$^2$ [g] |
| Capital cost[b] | | | |
| $ | 295. | 3100. | roughly 3.0 X $10^6$ [h] |
| $/KW | 1690. | 668. | 214 |
| Annual equiv. capital cost, mills/kwhr.[c] | | | 8.22[i] |
| no storage | 83.3 | 51.6 | |
| 1 day storage | 103.0 | 56.6[f] | |
| 2 day storage | 121.8 | | |
| 3 day storage | 141.0 | | |
| 5 day storage | 179.6 | | |
| Operation and Maintenance | ? | ? | about 4.0 |

[a] Installed capacities are rated at the high energy intensity level of 80 cal/cm$^2$,hr. (= 757 kwhr/ft$^2$,yr.)

[b] Capital cost is exclusive of storage for the thermoelectric and thermodynamic systems, but not for the solar pond.

[c] Annual equivalent capital cost is calculated using 6 percent interest with sinking fund depreciation. Different components of each system are evaluated using different expected useful lives. The term "1 day storage" means 24 hours of storage.

[d] Assuming 4 percent energy conversion efficiency.

[e] Computed by linear extropolation from the 10,000 kwhr output reported by Tabor with an available insulation of 185.0 kwhr/ft$^2$,yr.

[f] The Tabor thermodynamic unit includes only 16 kwhr of storage, which at the assumed rates of production will last 18 hours. A standby boiler and controls are included in the capital cost list above. The standby equipment can be obtained to burn any suitable fuel such as kerosene, gas, fuel oil, wood or agricultural wastes. Beyond the 16 kwhr of storage, the designers recommend use of the standby.

[g] Assuming 1½ percent energy conversion efficiency.

TABLE 5 (continued)

[h] Calculated by using Tabor's figure of $250,000. for the bare pond with free brine available, plus $200/KW for power generating equipment of the type required as in R. L. Hummel, "Power as a By-Product of Competitive Solar Distillation", United Nations, E/Conf. 35/S/15 (Rome, 1961). A twenty year life of these components was assumed.

[i] Storage and collector are combined in the solar pond. The thermal inertia of the pond is so great that no storage shortage can arise within a time period of weeks or perhaps months after the pond reaches an adequate temperature for operation.

Source: Thermoelectric System: Representative figures from questionnaire survey conducted by Richard A. Tybout and George O. G. Löf, Winter 1961-62.
Thermodynamic System: H. Tabor and L. Bronicki, "Small Turbine for Solar Energy Power Package", United Nations E/Conf. 35/S/54 (Rome, 1961), supplemented by personal correspondence.
Solar Pond: H. Tabor, "Large Area Solar Collectors (Solar Ponds) for Power Production" United Nations E/Conf. 35/S/47 (Rome, 1961), except as noted in footnote h.

The solar pond is not yet a technologically proven device. Also conceived by Dr. Tabor, the object is to suppress convection in a stationary pond of water and hence to use the water as an insulator over an artifical black bottom about 1-2 meters deep. To prevent heat transfer by convection, Dr. Tabor and his associates at the National Physical Laboratory of Israel have attempted to stabilize a density gradient of magnesium chloride or other suitable salt to have a high concentration (and high density) at the bottom tapering off to negligible concentration at the top. Numerous technological problems have been encountered,[52] among them the problem of extracting heat from the bottom while maintaining a tolerable temperature gradient. Prospective costs (contingent on technological success) are worth noting. The data are given in square kilometers of surface, indicating something of the size of an operating pond envisaged by its designers. If fresh water is at a premium, it would be possible (other problems solved) to combine distilled water production with electric power production to the economic advantage of both.

All of the solar power systems shown in Table 5 have costs at least one order of magnitude above those of nuclear power and even so are straining at the edge of the technically feasible. Strictly speaking, however, solar and nuclear power are not comparable because of differences in size. Also relevant is the fact that the technical manpower devoted to solar energy has been infinitesimal compared with that which has been devoted to nuclear power.

The small size of the solar power units places them in competition with diesel electric power. The cost of the latter in overseas installations is often relatively high. For example, as part of current efforts for the development of the Brazilian Northeast, a large number of diesel plants are being installed, ranging in size from 28 KW to 250 KW capacity.[53] The plan is to establish the same rates for electric power throughout the area regardless of the location of the diesel units. In point of fact, there is a fifty per cent variation in cost of diesel fuel among places to be served. The rate to be established is 46.3 mills/kwhr in the early years of the project, ultimately to be reduced to 36.9 mills/kwhr as higher use factors are obtained. With regional variations in diesel fuel costs, there are localities where the true costs are of the same order of magnitude as the Tabor unit, though a number of difficulties remain in making the comparison. For example, the dieselization program requires the training of large numbers of service mechanics. What would be the requirements with solar power? Anticipated daily use patterns do include night lighting in Northeast Brazil, but also important daytime loads. Similar findings apply to high diesel fuel areas of rural India. A full analysis of the comparison between diesel and solar power cannot be made here, but it is clear that solar power costs are of the right order of magnitude for certain applications in the small power field. If, as a nation, we are interested in the energy resource problems of less developed areas, it appears that solar power warrants increased attention. Enough has been said to show that its applications will be complementary with nuclear power from an economic development standpoint.

Solar Space Heat

The greatest potential bulk market that appears within reach of solar technologies is in space heating. As previously noted, approximately 20 per cent of all energy consumed in the United States is for space heat.[54] Putnam estimates that by year 2000, solar space heat will carry one-fifth the total comfort heating load.[55] One might infer that the prospects are at least as attractive at the same latitudes (north and south) throughout the world.

Solar space heat can be made available in greater or smaller degree by the architecture of a building without any special solar energy equipment. All buildings with south-facing windows (north-facing in the southern hemisphere) derive considerable direct heat from the sun. Design for capture of this portion of the total solar energy and design for other purposes are inextricably related. The same can be said of thermal insulation, of the heat absorbing qualities of interior furnishings and other attributes of any given structure. Overall optimization of architectural and solar heating design is required for each separate location, though for purposes of the broad general comparisons to be made herein, it is sufficient to consider a single standard dwelling in all locations.

A related complication is found in multiple outputs of the collector system. A solar hot water heating component is generally added to the space heater. Space cooling arrangements and facilities can be included. The result is to produce several outputs all of which use some parts of the solar equipment in common and all of which have their own incremental costs. Cost finding in such cases becomes complicated and some semi-arbitrary cost allocations cannot be avoided.

An entirely different kind of output that can be furnished by solar collectors is shelter. Solar collectors may constitute the roof and/or south wall of a building. In such cases, they furnish a shelter service that would otherwise require the construction of a conventional roof and/or wall. The shelter and energy outputs of the collector are different products with a common cost. It is appropriate to recognize this in calculating the cost of solar space heat.

The solar energy system to be analyzed in the present comparison avoids the problem of allocating costs among space heating, space coding and shelter by the simple expedient of including only a single output, heat, which is used for two purposes, space heating and hot water heating. The total useful heat for both purposes lumped together is evaluated at the cost of the solar energy system <u>less</u> the capital cost of a conventional furnace avoided. The solar energy "costs" so obtained are then compared directly with conventional fuel costs, for once correction has been made for the conventional furnace, the only other costs avoided by having solar heating is the fuel cost. Since solar heating requires a large capital investment and very low operation and maintenance expenses, this means that the annual fixed charge on capital again assumes crucial importance. The comparisons will be made using a 6 per cent imputed interest with sinking fund depreciation. No tax burden is assigned since solar heating is best for private residences, not for commercial buildings unless small (1 or 2 story) buildings are considered. Capital used for business purposes would have to be evaluated with due recognition of an additional tax responsibility.

Operation and maintenance on a solar energy system consist of electricity consumed, annual cleaning of the collector cover and whatever repairs are necessary. The system can be designed in such a way as to require very little maintenance and have a long life (25 years). Such a system is considered herein. Alternatively, a cheaper structure can be used, especially for the collector, at the expense of higher maintenance and shorter life. Then, the system is less capital intensive and more labor intensive. The higher the cost of capital relative to labor (one's own labor, if appropriate), the more economically efficient it is to use a cheaper, less durable collector.

Table 6 gives estimates of solar heat costs for hot water plus space heat in a standard (representative solar heated) house located in different parts of the United States. Costs shown in Part A are for a solar heating system in current use for heating a residence near Denver. The collector is mounted separately at a southernly tilt on a flat roof. The collector area is relatively small compared with house heating needs and, in fact, supplies only about one quarter of the heat required over the course of a year. A conventional auxiliary furnace supplies the remainder. Costs in Part A are given under two headings, "experimental" and "commercial." The experimental unit is the one actually in operation, except as noted in footnote f of the table. The commercial unit is of the same design as the experimental unit but with costs estimated for mass production of the parts and corresponding improvement in techniques of assembly and installation. The estimates have been carefully compiled but in their nature are subject to normal estimating errors.

TABLE 6

SOLAR HEAT COSTS

Part A
Colorado House Solar Heat Costs, dollars
(Collector Area = 530 square feet)

| Hot Water Components | Present Unit (Experimental) | | Prospective Unit (Commercial) | |
|---|---|---|---|---|
| Capital | | | | |
| Solar equipment | 250 | | 50 | |
| Assembly and installation | 150 | | 50 | |
| Standard gas heater | 230 | | 230 | |
| Total | 630 | | 330 | |
| **Space Heat and All Other Components** | | | | |
| Capital | | | | |
| Collector | 3200 | | 1200 | |
| Storage | 350[f] | | 350[f] | |
| Special controls and equipment | 1230 | | 200 | |
| Standard equipment | 730 | | 700 | |
| Assembly and installation | 3840 | | 800 | |
| Total | 9350 | | 3250 | |
| Saving on conventional furnace | -800 | -600 | -800 | -600 |
| Net capital cost | 8550 | 8750 | 2450 | 2650 |
| All Capital Costs | 9180 | 9380 | 2780 | 2980 |
| Annual equivalent capital costs[a] | 704. | 735. | 218. | 235. |
| Annual operating and maintenance | 20. | 20. | 20. | 20. |
| Annual Total | 724. | 755. | 238. | 255. |

Part B
Performance of Standard House with Long Term Average Insolation

| | Blue Hill Mass. | Medford Ore. | Columbia Mo. | Atlanta Ga. | Albuquerque N.M. |
|---|---|---|---|---|---|
| Degree days/yr.[b] | 6,392 | 4,547 | 5,113 | 2,826 | 4,389 |
| Conventional furnace saving, $ | 800 | 600 | 800 | 600 | 800 |
| Collector Area, $ft^2$ | 1,410 | 1,970 | 1,280 | 640 | 710 |
| Capital costs, $[c] | 5,780 | 8,090 | 5,280 | 3,070 | 3,130 |
| Annual costs, $ | | | | | |
| Equivalent annual capital costs[a] | 452 | 634 | 414 | 241 | 245 |
| Operation and maintenance[d] | 53 | 74 | 48 | 24 | 27 |
| Total | 505 | 708 | 462 | 265 | 272 |
| Insolation (tilted at latitude plus 15°) | 695 | 1,172 | 744 | 391 | 558 |
| Solar house heat supplied, $10^6$ BTU/yr. | 169.4 | 159.1 | 119.4 | 98.9 | 123.9 |
| Solar water heat supplied, $10^6$ BTU/yr. | 24.5 | 24.4 | 24.0 | 23.0 | 23.5 |
| Total solar heat supplied, $10^6$ BTU/yr. | 193.9 | 183.5 | 143.4 | 121.9 | 147.4 |
| Solar energy cost, $/$10^6$ BTU | 2.60 | 3.86 | 3.22 | 2.08 | 1.85 |

TABLE 6 (continued)

Part C
Conventional Fuel Costs, $/10^6 BTU[e]

| | Boston Mass. | Portland Ore. | St. Louis Mo. | Atlanta Ga. | Albuquerque N.M. |
|---|---|---|---|---|---|
| Anthracite | 1.86 | | | | not |
| Bituminous coal | | 2.22 | 1.33 | 1.53 | available |
| Fuel oil | 2.04 | 1.88 | 2.13 | | |
| Gas | 1.62 | 1.62 | 1.06 | 1.06 | |

[a] Calculated using 25 year expected life with sinking fund depreciation and 6 percent interest rate. Implicitly the same treatment is being given to capital saved on conventional furnace as to solar equipment capital.

[b] The number of degree days is computed by adding the differences between the average daily temperatures (in°F) and 65° F for all lower atmospheric temperatures.

[c] Capital costs are based on prospective commercial unit adjusted as follows: (1) collector plus assembly costs are assumed the same per square foot of collector area in all locations as in the Colorado house prospective commercial unit; (2) all other solar heating system costs (including both space and hot water heating) are assumed identical in all other locations as in the Colorado house prospective commercial unit; and (3) conventional furnace costs saved are subtracted in the indicated amounts from the total found in steps (1) and (2).

[d] Operation and maintenance costs based on Colorado house prospective commercial unit prorated by area of collector for each location.

[e] The following national average heat efficiencies were used: gas, 80 percent; anthracite, 62 percent; bituminous coal (stoker), 59 percent; oil, 57 percent; and bituminous coal (hand fired), 48 percent.

[f] 3,000 gal. water tank substituted for rock bed in actual use at Colorado house. Cost of tank provided by E. Speyer. See Source for Part B.

Source: Part A. Costs reported on experimental unit by owner of Colorado house, G. O. F. Löf, except as indicated by footnote f. Cost estimated for commercial production of same solar heating system by G. O. G. Löf.

Part B. Fundamental data on performance are from E. Speyer, "Optimum Storage of Heat with a Solar House", Solar Energy, Vol. III ( December, 1959), pp. 34-40. Costs are from Part A, as explained in footnotes.

Part C. American Gas Association, Gas Facts 1961-62, p. 238.

It will be noted that a standard gas heater is included with the solar hot water costs. This is an oversized heater that will serve the function of furnishing auxiliary heat in the fictitious house used as a standard (not in the actual Colorado house). Since our standard house has water storage of solar heat, the oversized hot water heater is connected in such a way as to deliver additional heat to the water in storage when, as and if needed.[56]

Part B is based on calculations made by Speyer for the standard house in different locations.[57] Speyer's calculations were based on average weather conditions month-by-month and took account of patterns of weather in sequence, insofar as such patterns are represented in averages.[58] Needless to say, different results would have been obtained if nonaveraged data had been used on an hour-to-hour or day-to-day basis. The object of design was to satisfy average weather requirements on the assumption that gas heat would be used for hot water during the months of December, January and half of February. The optimum storage capacity was found to be 3000 gallons of water in all locations shown, but collector area varied widely. The solar heating system used by Speyer was not completely described in his study, but was clearly representative of technologies in existence today.[59] It is used here to describe the performance of the solar heating system costed for the Colorado house in Part A.

The effect of different weather conditions on output are illustrated in Part B. Thus, the collector area required in Medford, Oregon is considerably greater than that in Blue Hill or Columbia despite the fact that Medford has a lower average number of degree days. This results from the high frequency of overcast winter skies in Medford. The more southern locations in the United States can achieve relatively greater advantage from solar heat, as exemplified by Atlanta, but the greatest advantage is in locations such as Albuquerque where a high heat demand, due to altitude above sea level in this case, is combined with a relatively low latitude and clear skies.

Part C in Table 6 gives the basis for an approximate cost comparison. Since capital investment in conventional furnace facilities has been subtracted from the capital costs of the solar heating systems, the remaining costs of solar heating capital are comparable to the fuel costs from conventional energy sources. The latter are shown in Part C of Table 6 for locations in the same climate areas used by Speyer (except for Albuquerque, for which fuel cost data were unavailable). The approximate nature of the comparison should be emphasized. The demands on the solar heating systems in different locations were a function of Speyer's standard house design. Architectural improvements would reduce the requirements of solar energy, but also the requirements for conventional heat. Differential effects of architectural changes could not be investigated in the present comparison.

The cost comparisons in Table 6 show that present technologies, even with the advantage of commercial production, do not offer as low a cost of heat as that afforded by commercial fuels in the special context of the comparison. Nevertheless, solar heat costs appear sufficiently close to conventional heat costs that any one of a number of circumstances could make solar heating economically attractive. A technological break-through in collector design would have the greatest effect. Short of this, the design of multiple purpose units that serve a shelter purpose and a space cooling purpose (where this last output has sufficient value to cover its own special equipment costs) would reduce space heating costs. Several such designs are in use in various experimental buildings, but they have not benefitted from the commercial scale of production assumed for the unit in Table 6.

The requirement of electrical energy to drive pumps and blowers reduces the prospects for use of solar space heat in less developed countries. Technologies combining solar power and solar space heat can, of course, be designed for use where electricity is not available, but with the disadvantageous position of solar power today, these would be of still higher cost. Fortunately, space heating demands are not as urgent as other kinds of energy demands in most underdeveloped areas.

Solar hot water heating, on the other hand, is already widely practiced. About 350,000 units were in use in Japan in 1961 and about 10,000 in Israel.[59] A large number of solar hot water heaters are found in North Africa and until gas became cheap in Florida, they were in frequent use there. Many are of the simple box type, quite inexpensive and, of course, subject to vicissitudes in the arrival of solar energy. The energy load carried by solar hot water heaters is small, but not to be ignored. Speyer assumed a hot water demand of 120 gallons per day heated to 140° F. Compare in Table 6 the relative heat needed to satisfy this demand with that required for space heating in the different locations, remembering that in Speyer's calculations the hot water load is satisfied by conventional fuel for $2\frac{1}{2}$ of the twelve months.

Solar Distillation

Several hundred small home solar distillers and quite a few of larger size are in operation in the arid regions of Mediterranean North Africa and the Near East. Others can be found, often on an experimental basis, elsewhere in the world. Representative costs have been estimated for three kinds of distillation technologies in Table 7. The small roof distiller is made of blackened asbestos cement with a glass cover. The tilted wick (Telkes) unit evaporates water from a replaceable terry cloth surface over which brine descends. The deep basin design evaporates by batch or continuous process from ponds filled to a depth of about 1 foot.[60] A number of other technologies are now under investigation, including forced convection systems, multiple effect evaporation and the use of inflatable plastic covers of various designs.

The data shown in Table 7 bring out once again the emphasis of solar technologies on small scale applications. Even at the relatively larger output of 100,000 gallons per day, solar distillation in the United States is more expensive than conventional fuel distillation. The costs of the latter have been estimated at an attainable level of $1.50 per thousand gallons at the 100,000 gallon per day output.[61] The costs of solar distillation are close enough, however, that communities in the Mediterranean area find it economically advantageous to install solar distillation facilities. Their calculations on this point are sometimes influenced by local unemployment (which can be used for solar plant construction) and the coincident problem of acquiring foreign exchange to finance fuel imports. The comparative advantage of solar energy in this case is analogous to that potentially existent for solar power applications.

Future Applications

There is ample prospect that nuclear power will be more widely used in the United States, hopefully with due recognition of its social costs as well as its economic benefits. It is also quite conceivable that solar energy will assume some of the space heating load in the American economy before the end of the twentieth century, but this depends on further technological progress.

In overseas areas, the significance of unconventional resources is comparatively greater. Conventional energy resources in this country show no signs of exhaustion in the foreseeable future or of experiencing important real cost increases before the end of the present century.[62] The same cannot be said of several other world regions.

Western Europe, the world's historic coal exporting region, is now a net importer of all fuels.[63] High density markets and high energy costs have given impetus to substantial programs for installation of nuclear power, in Britain and on the continent. The same logic applies to Japan.

Even more difficult is the energy resource position in which most of the less developed nations find themselves. The most serious energy resource problems are in prospect before the end of the twentieth century for the Latin American countries as a whole, for Asia except the Soviet Union and mainland China, and for Africa.[64] If the low income nations in these regions are to achieve the standards of living they

TABLE 7

ESTIMATED SOLAR DISTILLATION COSTS

(180 Kcal/cm$^2$, yr. global radiation on a horizontal surface = 194.5 kwhr/ft$^2$, yr. global radiation on a horizontal surface)

| | Roof Evaporator[a] | Tilted Wick Still[b] | Deep Basin Still[c] |
|---|---|---|---|
| Available radiation, kwhr/ft$^2$,yr. | 194.5 global, on horizontal surface | 226 global, on tilted surface[e] | 194.5 global, on horizontal surface |
| Size, ft$^2$ surface | 12.4 | 25 | 1.1 X $10^6$ |
| Output, average annual, gal/day | 1.435 | 4.21 | 100,000 |
| Capital cost, $ | 61.5 | 38.0 | 1.12 X $10^6$ |
| Expected life, years | 20 | 5-10 | 50 |
| Annual equivalent capital cost, $/1000[d] gal. | 10.27 | 5.88 - 3.36 | 1.95 |
| Operation and maintenance, $/1000 gal. | 4.00 | 1.63 | 0.263 |
| Total cost, $/1000 gal. | 14.27 | 7.51 - 4.99 | 2.21 |

[a] Representative costs based on hundreds of units already in use in Mediterranean North Africa.

[b] Costs of experimental units, 20 or 30 of which have been constructed. Costs could be expected to decline somewhat with volume production.

[c] Costs estimated by scale-up of 300 gallon per day experimental unit, taking advantage of minor technological improvements.

[d] Annual equivalent capital costs calculated using sinking fund depreciation with 6 percent interest.

[e] Tilted at fixed angle so that plane of surface is normal to solar beam at the equinoxes.

Source: Estimates were all derived from questionnaires circulated by Richard A. Tybout and George O. G. Löf in Winter, 1961-62.

so strongly desire, they will have to rely in part on fuel imports and/or expand their use of unconventional energy resources. Indeed, if they are to attain even moderate rates of per capita income growth, they must face the same choice.

Unfortunately, both atomic and solar energy involve capital intensive technologies. The scarcity of capital in less developed countries is well known. This fact works in favor of conventional fuel applications which, as we have noted throughout, are less capital intensive. Working in the counter direction, of course, is the expense of conventional fuel transportation, often over tedious overland ways. Where fuel imports are concerned, there is the additional disadvantage of foreign exchange problems. The value of foreign exchange is typically greater to a less developed country than is its domestic currency. Moreover, the ratio of the value of domestic currency to foreign exchange tends to be lower the lower the per capita gross national product of the country.[65] Not only does this fact work against conventional fuels, but it can work against nuclear power, most of the expenses of which require the use of foreign exchange.[66] A large part of the expense for solar equipment, on the other hand, can be met by domestic manufacture in less developed countries.

Additional insights can be obtained by considering the kinds of markets nuclear power and solar energy can serve. The high quality of nuclear electric power has been noted. It can be useful for the high density markets of new industrial centers and large urban areas. With some improvements in cost, solar energy can help the low density areas where cottage industry, village refrigeration, water pumping and like applications are the needs of the hour. The two unconventional energy resources are complementary insofar as their uses in less developed areas can be foreseen today.

Footnotes

1. J. R. Elizondo, "Prospection of Geothermal Fields and Investigations Necessary to Evaluate their Capacity," United Nations E/Conf. 35/GR/3(G), (Rome, 1961), p. 74.

2. P. C. Putnam, Energy in the Future (New York, 1953), p. 191.

3. R. A. Tybout, Atomic Power and Energy Resource Planning, Monograph 94, Ohio State University Bureau of Business Research (1958), pp. 21-22.

4. Jersey Central Power and Light Company, Report on Economic Analysis for Oyster Creek Nuclear Electric Generating Station (February 17, 1964).

5. U. S. Atomic Energy Commission, Civilian Nuclear Power, Appendices to a Report to the President - 1962 (Washington, 1962), p. 58, Table 4.

6. "Cooperative Power Reactor Demonstration Program, 1963," Hearings before the Subcommittee on Legislation of the Joint Committee on Atomic Energy, 88th Congress, 1st Session (July 9, August 7 and October 15, 1963), Exhibit A, Tables I and II, pp. 23-25.

7. See, for example, costs in the Cooperative Reactor Demonstration Program, "AEC Authorizing Legislation, Fiscal Year 1965," Hearings before the Joint Committee on Atomic Energy, 88th Congress, 2nd Session (February and March, 1964), Appendix 1.

8. For a discussion of social costs in the earlier nuclear power plants, see R. A. Tybout, "Atomic Power and the Public Interest," Land Economics, Vol. 34 (November, 1958), pp. 281-289.

9. General Public Utility power system, composed of financially integrated operating utilities.

10. The significance of "annual equivalent" capital costs is explained in the context of other methods of time discounting in R. A. Tybout, "Economic Criteria for Evaluating Power Technologies in Less Developed Countries," U. S. Papers Prepared for United Nations Conference on the Application of Science and Technology for the Benefit of Less Developed Areas, Vol. 1 (Washington, 1963), pp. 177-201.

11. See especially Philip Sporn, "A Post-Oyster Creek Evaluation of the Current Status of Nuclear Electric Generation," in Joint Committee on Atomic Energy, 88th Congress, 2nd Session, Nuclear Power Economics - Analysis and Comments - 1964 (Washington, 1964).

12. Federal Power Commission, Instructions for Estimating Electric Power Costs and Values, (Washington, 1960), p. 24. The FPC figure is made up of the following:

| | | Percent of Investment |
|---|---|---|
| Cost of money | | 6.75 |
| Depreciation, 6.75% sinking fund | | 0.77 |
| Interim replacements (straight line) | | 0.35 |
| Insurance (conventional plant) | | 0.25 |
| Taxes | | |
| Federal income | 3.40* | |
| Federal miscellaneous | 0.10 | |
| State and local | 2.35* | |
| Total taxes | | 5.85 |
| Total | | 13.97 |

*national averages

The above estimates are based on a plant life of 35 years. If reduced to a thirty year life, depreciation would be higher.

13. Op. cit., note 12, supra.

14. G. J. Strathakis, "Nuclear Power Drives Energy Costs Down," Electrical World (October 5, 1964).

15. The Oyster Creek insurance costs are included in operation and maintenance expenses for that plant as shown in Table 1. They are based on the provisions of the Price-Anderson Act.

16. See discussion by G. J. Strathakis, Op. cit., note 14, supra.

17. AEC Release No. E-292 dated August 23, 1962.

18. See "Private Ownership of Special Nuclear Materials," Hearings before the Subcommittee on Legislation of the Joint Committee on Atomic Energy, 88th Congress, 1st Session (July 30, 31 and August 1, 1963) and 88th Congress, 2nd Session (June 9, 10, 11, 15 and 25, 1964).

19. Calculated from Oyster Creek report (Op. cit, note 4, supra), using the 10.39 per cent capital charge there employed.

20. See Commissioner G. F. Tope, "Future Energy Needs and the Role of Nuclear Power," Third International Conference on the Peaceful Uses of Atomic Energy, Geneva, AEC Release dated August 31, 1964, page 4.

21. It is interesting to note that AEC simultaneously charges $43.00 a gram for the same plutonium isotopes in the same form if distributed for non-power uses (research and development or medical therapy). See AEC Release No. F-106, mimeographed, dated May 28, 1963. The inference is that the $10.00 price probably does not represent AEC costs.

22. A full statement of the environmental health problem by AEC follows: "When nuclear activities were small in scale, wastes involving very low specific activities could be discharged to the environment without unduly raising the radiation background level. Freedom to so dispose of them may be increasingly restricted in the future, primarily because of the rapidly increasing amounts and, secondarily, because acceptable environmental limits have been reduced. Hence, it will be necessary for the waste management research and development program to develop, on an expeditious basis, improved and more efficient methods for decontaminating large volumes of low-activity waste and concentrating the radioactive materials removed. In a related sphere, continued support must be given to environmental investigations to: (1) determine the ultimate fate of specific radionuclides in land, in water and in air environments; (2) establish reasonable technical criteria for safe disposal of very low level radioactive effluents into the environment. Such programs are, and must be, pushed with vigor." U. S. Atomic Energy Commission, Civilian Nuclear Power, A Report to the President, 1962 (Washington, 1962), p. 55.

23. Ibid., p. 55.

24. Ibid. Of high level waste disposal, AEC states, "The problem is technically soluble, but costs are not known." p. 55.

25. Op. cit., note 14, supra. The absolute values of his estimates are 4.21 mills/kwhr for a 600 MW plant and 10.37 for a 50 MW plant.

26. Yoram Barzel, "Productivity in the Electric Power Industry, 1929-1955," Review of Economics and Statistics, Vol. 45, (November, 1963), p. 402. This result is based on a cross-section analysis for 1959 of plants that commenced operation in 1953-1955. The sample size range was 28,000 to 1,400,000 kw. In a multiple regression analysis, Barzel reports a coefficient of logarithm of size of 0.109 and a coefficient of logarithm of load factor of 0.373. Both coefficients were highly significant in explaining variations in logarithm of plant productivity.

27. A fuller treatment of this subject will be found in W. Iulo, Electric Utilities - Costs and Performance (Washington State University Press, 1960).

28. Op. cit., note 4, supra, p. 24.

29. Using assumptions somewhat more simplified than those employed here, AEC has forecast a schedule of adoption of nuclear capacity. See Op. cit., note 5, supra, pp. 64-67.

30. S. H. Schurr and J. Marschak, Economic Aspects of Atomic Power (Princeton University Press, 1950).

31. Op. cit., note 5, p. 67. The estimate was reaffirmed by Commissioner Tope in his paper delivered at the Third International Conference on the Peaceful Uses of Atomic Energy in Geneva. See "Future Energy Needs and the Role of Nuclear Power," AEC Release, August 31, 1964.

32. National Planning Association, "Projections to the Years 1976 and 2000: Economic Growth, Population, Labor Force and Leisure, and Transportation," Report to the Outdoor Recreation Resources Review Commission (Washington, 1962), p. 132, Table D-1.

33. For a sample calculation in which derived effects are considered for nuclear power savings, see Schurr and Marschak, Op. cit., note 30, Supra, Ch. 13.

34. S. H. Schurr, B. C. Netschert and associates, Energy in the American Economy 1850-1975 (Johns-Hopkins University Press, 1960), p. 177.

35. Op. cit., note 30, supra, Ch. 12.

36. "A Treatise on Nuclear Propulsion in Surface Ships," prepared for the Chief of Naval Operations and submitted as appendix material in "Nuclear Propulsion for Naval Surface Vessels," Hearings before the Joint Committee on Atomic Energy, 88th Congress, 1st Session (October 30, 31, and November 13, 1963), p. 200.

37. Ibid.

38. Statement by Commissioner James T. Ramey, "Use of Nuclear Power for the Production of Fresh Water from Salt Water," Hearing before the Joint Committee on Atomic Energy, 88th Congress, Second Session (August 18, 1964), p. 3.

39. "Desalination of Water Using Conventional and Nuclear Energy," a report to the International Atomic Energy Agency, Vienna, 1964, included as Appendix A, "Use of Nuclear Power for the Production of Fresh Water from Salt Water," Op. cit., note 38, supra, p. 61.

40. Ibid., pp. 49-50.

41. Ibid., p. 86. With an overall national average consumption of water in the United States of 1700 gallons per day per person for all uses, there are certain sea-coast metropolitan areas where the demand would be sufficient to consume the output of a billion gallon per day plant.

42. Idem.

43. P. C. Putnam, Op. cit., note 2, supra, p. 198.

44. S. H. Schurr, B. C. Netschert and associates, Op. cit., note 34, supra, p. 234, Table 64.

45. R. A. Tybout, Op. cit., note 3, supra, Table 1, p. 6.

46. Reported in "Integrating Nuclear Power into National Grids," Nucleonics, Vol. 22 (October, 1964), p. 59.

47. Compare H. E. Landsberg, "Solar Radiation at the Earth's Surface," Solar Energy, Vol. V (July-September, 1961), pp. 95-98.

48. Such an analysis is being conducted by the author using computer simulation and equipment performance characteristics supplied by his collaborator Dr. George O. G. Löf. Five categories of equipment are being evaluated using U. S. Weather Bureau data for eight climates representing all major world climates in the temperate and tropical regions except for "tropical rain forest," for which adequate data are not available.

49. The subject is being investigated by the author, but more meaningful conclusions cannot be drawn at the present time.

50. These relationships, and the problems of determining direct and diffuse radiation intensities from data reported by the U. S. Weather Bureau, will be discussed by the author in a forthcoming paper, "Statistical Separation of Direct and Diffuse Solar Radiation."

51. H. Tabor and L. Bronicki, "Small Turbine for Solar Energy Power Package," United Nations E/Conf. 35/S/54 (Rome, 1961).

52. H. Tabor, "Large Area Solar Collectors (Solar Ponds) for Power Production," United Nations E/Conf. 35/S/47 (Rome, 1961).

53. Information which follows has been obtained from a number of different sources, including especially The Ford Foundation office in Rio de Janeiro, and is summarized here from unpublished materials on the economics of solar energy.

54. Note 34, supra.

55. P. C. Putnam, Op. cit., note 2, supra, p. 181.

56. A design for this purpose is given in A. Whillier, "Contribution to Solar House Heating - A Panel Discussion," Proceedings of World Symposium on Applied Solar Energy (Phoenix, Arizona, 1955) and in "Principles of Solar House Design," Progressive Architecture, Vol. 36 (1955), pp. 122-126.

57. E. Speyer, "Optimum Storage of Heat with a Solar House," Solar Energy, Vol. 3 (December, 1959), pp. 24-48.

58. See discussion by Speyer, Ibid., p. 29.

59. I. Oshida, "Uses of Solar Energy for Water Heating," United Nations E/Conf. 35/GR/13(S) (Rome, 1961), (rapporteur's report of session III.C.1).

60. The technologies represented here are described in many reports. For an early summary, see G. O. G. Löf, "Demineralization of Saline Water with Solar Energy," Saline Water Research and Development Progress Report No. 4, U. S. Department of the Interior (Washington, 1954). See also M. Telkes "Solar Still Construction," Office of Saline Water, Progress Report No. 33, U. S. Department of the Interior (Washington, 1959) and papers submitted in Session III-E, United Nations Conference on New Sources of Energy (Rome, 1961).

61. Estimate by U. S. Office of Saline Water, "Use of Nuclear Power for the Production of Fresh Water from Salt Water," op. cit., note 38, supra, pp. 82-86.

62. The magnitudes of prospective real cost increases are shown in R. A. Tybout, Op. cit., note 3, supra, Ch. 1.

63. Fuel export and import data are reported in United Nations Statistical Series J-7, Tables 3, 8, 9, 11 (serial publication).

64. See R. A. Tybout, Op. cit., note 3, supra, Table 6 and related discussion.

65. P. N. Rosenstein-Rodan, "International Aid to Underdeveloped Countries," Review of Economics and Statistics, Vol. 43 (May, 1961).

66. For a discussion of AEC policies to alleviate this problem, see Commissioner J. T. Ramey, "The U. S. Program for Advancing International Atomic Power," Nucleonics, Vol. 22 (July, 1964) and an interview with AEC Chairman G. T. Seaborg in the same issue.