Energy Strategies for India:
A Technological Perspective

by

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Foreword

Energy always has been a pivotal and costly input to the development process. The 1973-74 explosion of oil prices has made the energy issue -- alternative efficient forms, conservation, etc. -- all the more salient for the poor countries. For a year and a half some of us in Princeton's Center for Environmental Studies and Research Program in Development Studies have been talking about possible ways of usefully engaging this issue in some of the poorest countries, namely, those of South Asia. A factor stimulating our interest has been the presence of Dr. Vikram L. Dalal, a Princeton Ph.D. in Electrical Engineering and more recently an M.P.A. graduate in applied economics from the Woodrow Wilson School. After some years as a research scientist for R.C.A., working in part on macro energy and environment matters in the United States, Dr. Dalal during the past years, part of the time as a Research Associate in R.P.D.S., has been turning his attention to the energy problems of developing countries, especially his native India.

Sitting in Princeton, the interested group in general and Dr. Dalal in particular were inhibited by lack of sufficient knowledge of what is now going on or taking shape in India in the way of new energy-related research, socio-economic as well as technical. Moreover, after a number of soundings in Washington and elsewhere, we became persuaded that no one on this side of the water had that picture adequately in view, especially with regard to less orthodox, more "exotic" energy technologies (in which Dr. Dalal, himself a particular expert on solar energy, is especially interested). And knowing the size and complexities of India and the newness of some of the initiatives there, we suspected that a knowledgeable, fairly comprehensive, on-the-scene snapshot of the present state of Indian
R&D activity on energy might even add usefully to the ready availability of such information there.

Thus we were delighted when, last December, the Ford Foundation, with remarkably little bureaucratic emptying and hawing, retained Dr. Dalal to undertake just such a survey over the space of seven weeks from late January to early March. It would have been impossible for Dalal to have accomplished as much as he did in that time if he did not already know the country and were not already deeply -- thoughtfully as well as technically -- immersed in the subject matter. But even so it required excellent cooperation from many Indian colleagues and good logistical support from the Foundation as well as an outstanding effort by Dalal to produce the result.

In his report Dr. Dalal has by no means suppressed his own ideas or opinions; nor has he been diffident about rendering assessments of weakness, as well as strengths in current Indian programs. Yet (just as, by all accounts, he did in the course of the trip itself) he achieves a synthesis that few will find abrasive at the same time that many are finding it exceptionally informative, stimulating -- and useful.

Dr. Dalal's views, it should be routinely noted, are indeed his own; they are not necessarily those of the Ford Foundation, C.E.S., or R.P.D.S.
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Preface

This study is the outgrowth of work on energy strategies for India that I have been carrying on for the last two years at Princeton University. This effort was jointly sponsored by the Research Program in Development Studies, and the Center for Environmental Studies. My background in solar energy research and energy economics had convinced me that the utilization of solar energy was much nearer economic feasibility than the policy makers, both in India and the U.S., believed. In particular, solar energy for irrigation and for electric power generation (central stations) seemed feasible technologies with particular relevance to a nation like India, blessed with direct sunshine nine months a year. Simple calculations also led me to believe that biogasification of organic waste seemed very promising for meeting India's rural needs. The publication of the Ford Foundation Study on "Energy and Agriculture in the Third World" strongly reinforced that feeling. I also became aware that the only way really to assess the potential for solar energy and biogasification was to go to India and talk with people directly involved in policy formulation, and even more important, talk with the scientists actually involved in research and development in these fields.

I am very happy that the Ford Foundation, which has always had a strong interest in promoting agricultural and rural development in India, provided the opportunity for me to do this "field" research, and I am very grateful to the Foundation, particularly Dr. Vijay Pande, Mr. Harry Wilhelm and Mr. Eugene Staples, for their encouragement and support. Particular thanks are also due Professor John Lewis of Princeton University for his unflagging support and encouragement in this study and for laying
the groundwork for me before I even reached India. Professor Robert
Socolow, of Princeton, also deserves special thanks for his interest in
this study, and for his support of my stay at Princeton.

There are many other people in India without whose help and
kindness this work could not have been done. Particular thanks are due
Dr. Ashok Khosla of the Department of Science and Technology, Dr. Kirit
Parikh of ISI, Dr. Amarjeet Singh of CEERI, Dr. Sharan of BHEL, Dr. S.V.
Warlu of CEL, Dr. Verma of NPL, Dr. Mishra of SSPL, Dr. Bhosle of PRL,
Dr. K. Ramanathan of TIFR and Dr. K. Hinge of TERI. I also wish to thank
Professor Nayudamma, Director of CSIR, Dr. Swaminathan, Director of ICAR,
Mr. R. Bhargava, Joint Secretary, Ministry of Energy, and Mr. C.C. Patel,
Addnl. Secretary, Ministry of Irrigation for patiently listening to my
ideas and encouraging and helping me in my work. Special thanks are due
my father, L.R. Dalal, Chief Secretary, Gujarat, for helping and guiding
me in my research, and for offering many valuable suggestions.

The above list is by no means exhaustive. There are many,
many others who helped with a great deal of enthusiasm and often gave
me important ideas. It is no exaggeration to say that this time I
spent in India was one of the most intellectually stimulating periods
of my life. I can only hope that the report reflects accurately the
enthusiasm and creativity of the scientists in India.

Needless to say, there are probably some errors in this report.
I acknowledge full responsibility for all such errors, whether of judgment
or fact. I also acknowledge all responsibility for the views expressed
in this report, and in no manner should this report be construed to
represent the views of the Ford Foundation. The Ford Foundation
provided the opportunity — the views are my own, and not the Foundation's.

Finally, thanks are due the staff of the Ford Foundation for handling the routine chores most efficiently — particularly to Mrs. Kiran Arora, Mrs. Swarn Harwah and Mr. Khurana.
Energy Strategies for India: An Assessment of New Technologies

Dr. Vikram Dalal

Summary

The increase in the price of oil has drastically altered the energy strategies facing India. In particular, the efficient utilization of India's abundant energy resources, solar energy, nuclear fuel and coal has become a high priority consideration. This report examines the technology and economics of solar energy and better coal utilization. Strategies for effective energy conservation are also examined. The major conclusions are:

1. **Solar Energy**: The technologies for solar energy utilization in India are well developed, and require no major technological breakthroughs. They are simple, and in many cases, economical. Solar energy is particularly appropriate for rural energy use. In particular, the following technologies appear to be most appropriate for India:

   - **Fuel production**: High yield forestry for village woodlots, providing fuel for villagers, fodder for cattle, and also reducing soil erosion, appears feasible and economical, and should be a high priority strategy.

   - **Solar Thermal Systems**: Solar hot water heaters for industrial use, solar cookers, solar distillation for the provision of drinking water, simple solar heating systems for rural applications, solar crop drying and solar sky-therm air-conditioning appear to be the most appropriate solar-thermal applications for India. There is a particular need for higher temperature heat raising, using simple concentrators.
C. Solar Electrification: Contrary to generally accepted wisdom, solar electrification seems both practical and economically feasible in India, using existing technology. In particular, high intensity Silicon solar cells appear very promising for rural electrification and irrigation. High temperature solar-thermal-electric systems, using field of mirrors concentrating solar energy on a tower, appear feasible and promising for central station application in Western India. Solar-electric irrigation is probably more promising and cheaper than mechanical solar pumps.

2. Biogasification of Organic Waste: High-efficiency biogasification of organic waste is an extremely appropriate technology for rural application in India. High-efficiency biogas plants have the potential to provide all of the cooking needs of a typical village, and still have energy left over to provide electric power using modified diesel engines for irrigation, rural lighting, educational TV sets and village industries. The biogas plants can be economical even if cooking gas is given away for free, provided high efficiency is achieved (400-500 l of gas/kg of dry manure) and the fertilizer output is sold. Community plants appear to have a distinct economical and efficiency advantage over household plants. Similarly, urban waste has a significant energy and fertilizer potential, and the plants utilizing waste should be both feasible and practical.

3. Coal Utilization: New technologies for coal combustion, particularly low BTU gasification, fluidized bed combustion and co-generation of power and chemicals using coal-gas appear very promising and feasible in certain locations in India. Combined-cycle plants utilizing coal-gas have the
promise of higher efficiency and better load factors for a smaller size unit than for a coal fired boiler, and appear feasible for dispersed generation.

4. Energy Conservation: Energy conservation is an extremely important consideration for India. There is an enormous potential for energy conservation in the industrial and power generation sectors in India, amounting to a saving of 50-100 million tons of coal per year in 1991. Co-generation of power and steam for industrial processes appear feasible in certain locations, thus further saving energy. Energy savings in transportation also seem feasible. In particular, dieselization of automobiles, creation of bus lanes, systems analysis of transportation and dieselization and electrification of railroads are important strategies for India.

The status of Research and Development efforts in India in these fields is also examined in this report. It is found that the scientific and technical base is well established, that very high degrees of talent and enthusiasm exists, and that the scientists are well aware of the potential and problems of these "new" technologies. The major weakness seems to be at the policy making level. There seems to be a waste of resources among too many marginal R&D efforts, a lack of criticality in any one technology, and a reluctance to support large-scale field trials of the more promising technologies. There is no hope of commercialization of new technology without realistic pilot-plant testing.

The role of external aid agencies is also examined. The areas of applicability appear to be in scientific exchange, while supply of initial equipment so necessary for a rapid progress in new technologies, and above all, in funding large-scale field trials of the more promising
technologies. In particular, the World Bank should support new promising technologies, or the economic resource limitations within India may prevent such technologies from becoming commercial. The UNDP also has an important role to play in this area, as do the development funds of OPEC and industrialized nations.
I. Introduction

Energy is an important resource in modern economies. In industrialized countries, energy is used for industrial activity, transportation, agriculture and for comfort conditioning. In the less developed countries such as India, the major uses of energy are for domestic use (cooking), industrial activity, public and freight transportation and agricultural production, particularly for irrigation and fertilizer production. In India very little energy is used for luxuries such as air conditioning or home heating, or for private transportation.

The importance of energy to the economic development process is shown by the energy consumed per unit of output in India. India used nearly twice as much energy per unit of output \(31 \times 10^3\) kCal/$ in 1971\(^1\) as the U.S. \(15 \times 10^3\) kCal/$. Of course, the per capita use was much lower in India than in the U.S. \((0.25 \times 10^6\) kCal/capita in India; \(8.5 \times 10^6\) kCal/capita in the U.S.). The importance of energy to India's economy can also be seen from the fact that the growth rate of "commercial" energy in India has been 7%/year for two decades (1953-1972), as opposed to 3.2%/year in the U.S. (Commercial Energy is energy produced from commercial fuels -- coal, oil, gas, electricity, etc. In contrast to these fuels, most of the fuel consumed in rural India is free or non-commercial -- dried cow dung, fire wood, vegetable wastes).

The sharp increases in the price of oil since 1973 (500% in 2 years) have had a severe impact on the economy of India. India had relied on Persian Gulf oil for an important share of its energy supplies. But the increase in the oil bill has forced India to curtail its oil imports in order to meet balance-of-payments constraints. In many parts of India
Irrigation pumps were standing idle because of the lack of power or diesel oil. The shortages of power, partly due to poor rainfalls, also forced curtailment of industrial activity in many parts of India. Fertilizer availability had also been reduced.

The combined effects of these energy and fertilizer shortages have been disastrous to India's economy. For example, agriculture, in particular the production of winter crops (such as wheat) which rely on irrigation and use fertilizer intensively, suffered during 1973 and 1974.

The sharply increased price of oil has forced a general reappraisal of India's energy strategies for the coming decades. While the direction of movement as far as utilization of conventional energy resources (coal, oil, hydroelectricity) is fairly clear and has been dealt with extensively in the report of the Fuel Policy Committee, the utilization of more unconventional resources such as solar energy, biogasification, wind power, etc., is generally thought to present problems which may require intensive research and development before practical sources can be developed. Even better utilization of coal, using innovative technologies such as gasification, is considered to be "futuristic."

This study addresses itself to strategies for utilization of unconventional energy sources, and assesses the state of research and development which is going on in India on solar energy, biogasification, wind energy and coal conversion.

In any study on energy, it is very important to keep in mind that the demand for energy is dependent upon prices and technology. A realistic energy policy must recognize that economically feasible energy conservation strategies are available, and are particularly appropriate
for a rapidly growing country, because they can be implemented best in new plants and equipment. This study also addresses itself to possible energy conservation strategies for India, and assesses the state of R&D in India on energy conservation.

It is also important to note that R&D do not progress in a vacuum. They require careful nurturing, encouragement and support. Also, rapidity of R&D progress depends on the ability of the policy makers to recognize potential breakthroughs and to allocate funds. Commercial feasibility depends critically on the willingness of policy makers to take educated risks and to allocate substantial sums of money for pilot plants for the more promising technologies. This study also addresses the status of R&D policymaking in India in the field of energy.

It is important to keep in mind that India is a vast and diverse country. In Figure 1, we show the map of India. The land area of India is approximately 2.5 million km$^2$. The climate varies from the desert of Rajasthan in western India, to the extremely heavy rainfall (1000 cm/year) regions of eastern Assam in Eastern India. Over most of the country, though, the rainfall is about 50-100 cm/year, and comes during the monsoon the months of July-September. During/remaining 9 months of the year, the sun shines brightly just about every day over most of India, with a few days of rainfall (light drizzle) in the north (Punjab, UP region) in January and February. Thus, India is blessed with strong sunshine for 9 months, a point which will become important in our discussion of solar energy.

II. Utilization of Energy in India

In order to understand the energy needs of India, it is useful to look at how energy is used in India. In Table I, we show the amount
of energy used in 1971 by each major sector of India's economy, both as
to absolute units (k Cal) and as % of total. (It is useful to remember
that 1 kg of coal equals 5000 k Cal.) We also show the annual compound
growth rate (for period 1953-1971) for each of these sectors.

It is important to note that even now, 57% of the energy use in
India is in the rural domestic sector. The very high growth rate in
agricultural energy sector is also worth noting, thus, clearly, provision
of rural energy needs should be a primary aim of any energy strategy for
India.

<table>
<thead>
<tr>
<th>Sector</th>
<th>$10^{12}$ kC</th>
<th>% of Total</th>
<th>% Growth Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industry</td>
<td>345</td>
<td>22.4</td>
<td>7.5</td>
</tr>
<tr>
<td>Transportation</td>
<td>160</td>
<td>10.4</td>
<td>4.5</td>
</tr>
<tr>
<td>Government and commercial</td>
<td>35</td>
<td>2.3</td>
<td>8.6</td>
</tr>
<tr>
<td>Agriculture</td>
<td>30</td>
<td>2.0</td>
<td>12.7</td>
</tr>
<tr>
<td>Urban domestic</td>
<td>83</td>
<td>5.3</td>
<td>6.1</td>
</tr>
<tr>
<td>Rural domestic</td>
<td>890</td>
<td>57.4</td>
<td>2.2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1542</strong></td>
<td><strong>100</strong></td>
<td></td>
</tr>
</tbody>
</table>

(Source: Fuel Policy Committee (1974))

It is also worth noting that while the index of industrial activity
increased by 42% over the decade of 1960's the energy consumption in industry
increased by 97% over the same period. So, clearly, energy use per unit of
industrial output is increasing. This is characteristic of developing
economies. As they develop, their industrial base shifts from low energy-
intensive industries such as textiles to high energy-intensive industries
such as chemicals and aluminum. In contrast, in the more developed economy of the U.S., the energy use per unit of industrial output decreased from 1960 to 1970, reflecting a mature economy and technological improvements. There is every reason to believe that the sharply increased price of energy will lead to even more savings in energy per unit of output in the U.S.

In many respects, the crucial sector for India's development is agriculture. The development of HYV wheat and, to a lesser extent, rice and jowar, have given a real boost to agricultural productivity in India. Yields of wheat have increased from 1 t/ha to over 3 t/ha in Punjab and Haryana. The green revolution is critically dependent upon the supply of water by irrigation and upon fertilizers and insecticides. For certain crops, the use of tractors may also be necessary in order to plow the hard-baked ground. High yield agriculture, at least at present, demands water in the right quantity, and at the right time. Since over most of India there is almost no rainfall from October through May, the winter wheat crop, in particular, needs irrigation water. Sugar cane, which has a long growing season, also requires irrigation. Even in September a prolonged dry spell can damage the rice crop, which may need irrigation to save it.

While canal irrigation is feasible in many parts of India, the bulk of the Ganga plain has no easy access to canal water. On the other hand, the Ganga plain has one of the largest reservoirs of ground water in the world. Greater tapping of this reservoir would not only irrigate approximately 30-40 million hectares; it would also lower the water table, thereby accommodating more rainwater during the monsoon and lessening the intensity of floods. Ground-water pumping, of course, requires energy.
To give an example, if 30 million hectares were irrigated with ground water, we know that it is possible to produce 90–120 million tons of wheat under proper conditions. This would quadruple India’s wheat production, leading to a higher nutrition level. Wheat demands about 4000 m$^3$ of water per hectare. If this water were raised from 30M depth, the energy demand would be 600 kwh/ha. For 30 million hectares, then, the demand would be $1.8 \times 10^9$ kwh. Considering 1000 hours/year, (for the wheat crop), this translates into 18,000 MW power station, or almost 90% of the total power capacity in India today. This large power demand, which is a peak-demand, is one reason why many farmers in many parts of India do not get power during the day time. Some progressive farmers are reluctant to irrigate at night, particularly the wheat crop, because they want to keep a close watch on the crop as it is being irrigated and attend to weeding, etc. Provision of guaranteed power to farmers is one of the most important characteristics that any energy strategy must meet. As will be seen later, this is one of the virtues of solar energy.

Fertilizer needs for agriculture are also energy-intensive. To produce HYV wheat, 40–60 kg of N is needed per hectare. Thus, 30 million hectares would require $1.8 \times 10^6$ t of N. Using 2 t of N/t of naphtha, we come up with $\sim 1 \times 10^6$ t of naphtha, or an energy equivalent of $12 \times 10^9$ kwh (2000 MW power plant, 6000 hs/year). Clearly, energy demands for fertilizers are large. Any energy strategy for India must pay careful attention to the provision of fertilizers, and any strategy which produces organic fertilizer with minimum energy consumption, deserves a careful consideration. As will be seen later, biogasification may be one such strategy.
Finally, India is embarked upon a very ambitious strategy for rural electrification. The social benefits of rural electrification are very great, ranging from increased education, reduced population growth, and, through the satellite educational television, an additional means of providing extension services for the farmers. The economic benefits, of course, include the provision of energy for irrigation and for small industry. Today 150,000 villages in India have been electrified (though some have only minimal electrification) out of a total of 565,000 villages. However, the electrification has only penetrated the larger villages, and the bulk of India's villages (65%), which have very low populations (less than 500), have scarcely been touched by electrification (only 11% of these small villages were electrified as of 1974). The reasons are obvious. Electrification from central generation requires long distribution lines to reach the smaller, more remote, villages. The very low load factors (10-20%) in villages cannot justify laying these lines. Therefore, an economical technology for dispersed generation has an enormous potential in India. Solar energy and biogasification may provide such technologies.

To give an example of the potential market for dispersed generation, if each smaller village had 200, 50W lightbulbs (2 per household) and 2 television sets, each with 200W load, the power required would be 10 kW per village. If the industry and irrigation drew another 90 kW, total power would be 100 kW/village, or a total of $35 \times 10^3$ MW for 350,000 villages, 70% more power than India's capacity today. The potential rural demand is very large.
III. Energy Resources of India

The major energy resources of India are coal, oil, gas, firewood, animal and vegetable waste and solar and wind energy. The total energy resources are shown in Table II. I also show the annual consumption of each fuel.

Table II

<table>
<thead>
<tr>
<th>Energy Resources of India</th>
<th>k Cal</th>
<th>Annual Consumption (1974)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Coal</td>
<td>$1.0 \times 10^9$ t</td>
<td>$5 \times 10^{17}$</td>
</tr>
<tr>
<td>2. Oil</td>
<td>$2.4 \times 10^9$ t</td>
<td>$2.4 \times 10^{16}$</td>
</tr>
<tr>
<td>3. Gas</td>
<td>$200 \times 10^9$ m$^3$</td>
<td>$1.8 \times 10^{15}$</td>
</tr>
<tr>
<td>4. Hydroelectric</td>
<td>$216 \times 10^9$ kwh</td>
<td>$2 \times 10^{14}$</td>
</tr>
<tr>
<td>5. Nuclear fuels (Th, U)</td>
<td>$500 \times 10^3$ t</td>
<td>$6 \times 10^{18}$</td>
</tr>
<tr>
<td>6. Solar</td>
<td>$6 \times 10^{18}$ kC</td>
<td>$6 \times 10^{18}$</td>
</tr>
<tr>
<td>7. Firewood</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Animal waste</td>
<td>$300 \times 10^6$ t</td>
<td>$620 \times 10^{12}$</td>
</tr>
</tbody>
</table>

*Solar energy utilization includes firewood and animal waste.


A look at Table II makes it obvious that the largest proven energy resource of India are solar energy, coal and nuclear fuel. While the probable oil reserves are high ($2.4 \times 10^9$ t)$^{10}$ the proven reserves are much less ($\approx 400 \times 10^6$ t). Even the recent Bombay-High field is thought to contain only about $200 \times 10^6$ t of oil, or a production of 10 million tons a year. India needs about five Bombay highs before it can become
self-sufficient in oil. In any event, even if India had four billion tons of oil, at 5.5% growth rate (the rate projected by Fuel Policy Committee) this would be used up in 38 years, or by 2012. (Two billion tons would be used up in 29 years, or by 2003.) India’s past growth rate in oil has been 9.5%. At this rate, four billion tons would be gone in 30 years, or by 2004. Thus, oil is simply not going to be around much after the current century. Oil, in any event, is an invaluable feedstock for petrochemicals, and it is a great waste to burn it for fuel.

IV. Energy conservation

Energy conservation in the broadest sense includes elimination of waste and better utilization of energy in every sector. Energy conservation is absolutely vital for a fast-growing, capital-poor economy. Energy production facilities are very expensive in terms of capital requirements. Thus, nuclear power plants may cost as much as Rs. 10000/kw, or Rs. 10 billion for a 1000 MW plant. In India, energy production facilities (mines, oil drilling, power generation, investments in railways, transmission lines, etc.) account for almost 30% of the total investment in capital goods. Clearly, energy conservation is a very important aspect of India’s energy strategies.


Since the energy consumption in industry is expected to account for the lion’s share of energy utilization in 1990-91 (The FPC projects 2000 \times 10^{12} \text{ kc} in 1990-91 for industry, 47% of total energy consumption), energy conservation has to start in industry. Industry is also the sector in which energy conservation is the easiest to achieve. A recent study in the U.S. claims an overall saving potential of 23% (per unit of output)
by better utilization of energy in industrial sector. An industrial process does not generally require a fixed energy input per unit of output. Process modifications can reduce energy input. These process modifications are easiest to incorporate in new plants. In addition, existing plants can incorporate such simple modifications as heat recuperation, better atomization and flame turbulence to achieve perhaps 10% savings in energy at minimal cost. In the U.S., such savings are already a reality and some of the larger companies such as Dow Chemical, DuPont and RCA have achieved even larger savings, in some cases amounting to 30% per unit of output. Perhaps, the best indication of the feasibility of energy conservation in industry is the proliferation of consulting engineering firms which offer their services to U.S. industry for reducing energy use. Even DuPont, the largest chemical firm in the U.S., offers consultancy services to U.S. industries in the field of energy conservation.

The potential savings in six key industries in the U.S., using known 1973 technology are shown in Table III.

<table>
<thead>
<tr>
<th>Industry</th>
<th>Specific Fuel Cons.</th>
<th>% Savings over 1968</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In 1968</td>
<td>Potential with Process Improvements</td>
</tr>
<tr>
<td>Iron &amp; Steel</td>
<td>7.3</td>
<td>4.7</td>
</tr>
<tr>
<td>Petroleum Refining</td>
<td>1.2</td>
<td>.9</td>
</tr>
<tr>
<td>Paper</td>
<td>10.7</td>
<td>6.5</td>
</tr>
<tr>
<td>Aluminum</td>
<td>42.6</td>
<td>29.1</td>
</tr>
<tr>
<td>Copper</td>
<td>7.1</td>
<td>5.0</td>
</tr>
<tr>
<td>Cement</td>
<td>2.2</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Source: Ref. 11
Note, of course, that these savings, which are very large, may not necessarily be economical. But there is little doubt that the very high price of energy will make many of these new processes economical, and that substantial savings will be realized, even though they may fall short of the numbers in Table III.

To illustrate the potential impact of energy conservation in industry, if a 25% saving were possible in 1990-91, this would result in a saving of $500 \times 10^{12}$ kC, or equivalent of 100 million tons of coal. In terms of investment in coal alone, this is Rs. 6 billion saved. In addition, there are savings in the transportation of coal and electricity. According to the Fuel Policy Committee, $210 \times 10^9$ kWh would be used by industry in 1990-91. A saving of 25% would be $52 \times 10^9$ kWh. At 60% plant factor, this is a saving of 9000 MW, or an investment cost of Rs. 27 billion (at Rs. 3000/kW). Surely, these potential savings are so large that India cannot afford to ignore energy conservation as a high priority strategy.

Apart from process modifications, an attractive way of saving energy is co-generation of steam and electricity. Many industries use steam at 200 PSI pressure. Why not generate electricity at 1200 PSI steam, using back-pressure turbines, and then feed steam at 100-200 PSI to neighboring industries? There are many locations in India where this "total energy concept" is applicable even today. Examples are Bombay, Baroda, Ahmedabad, Asansol, Durgapur. To give a concrete example, textile industries in Bombay are concentrated in a narrow area near Parel. Each of them burns oil or coal to generate steam for its own use. A central generator could easily provide the process steam to these mills, and achieve an overall thermal efficiency of perhaps 60-70% as opposed to 33% for power generation alone.
The total energy concept is particularly appropriate for the industrial parks which are being set up all over India. For example, Delhi has Gaziabad and Faridabad complexes. In these new complexes, total energy systems should be considered as potentially viable systems.

B. Energy Conservation in Transportation.

It is well known that the steam locomotives are very inefficient with thermal efficiencies of perhaps 10%. As opposed to this, diesel locomotives can approach 35-38% efficiency. In addition, a ton of diesel oil has more energy than a ton of coal (transport saving) and diesel can be transported by pipelines at a fraction of the energy cost of rail transport. Thus, diesel oil is much more efficient fuel for rail transport than coal.

The question, of course, arises: where does India get diesel oil? Nevertheless, it is foolish not to use imported oil for the purpose for which it is best suited — namely transportation. The coal saved can be utilized much more efficiently for mine-mouth power generation, or fertilizer production, or industrial use, replacing oil for such applications.

In addition to importing oil, India can make oil from coal. The overall efficiency for rail transport is still about 30%, compared to 10% for direct coal use. (Coal liquefaction may well be economical for India.)

One of the largest potential saving in energy use is in urban transport. A bus is perhaps 5-6 times more energy efficient (passenger-km/kC) than even a small car. Moreover, it creates for less congestion than a car per passenger km. (Reduction of congestion will lead to increase in efficiency.) In large cities such as Bombay, Calcutta, Delhi, and
Ahmedabad, where traffic congestion is severe at certain times of the day, creation of special lanes (or roads) for buses will speed up traffic, utilize capital equipment more efficiently, lead to reduced air pollution and shift traffic from cars to buses. This is no idle speculation. Results similar to the above have been achieved in places like San Francisco, New York and Washington. Urban planners in India must address this question on an urgent basis. Perhaps it is even easier to implement these decisions in India than in the U.S., because of lack of cross-jurisdictional urban disputes and the centrality of municipal governments.

Another potential large saving in the transportation sector lies in dieselization of all future automobiles. It is well known that a diesel may be 50% more efficient than a petrol engine. The problems with diesel engines which have prevented their popularization in the U.S. (slow acceleration, hard-starting in very cold weather) have little relevance in India. The diesel engine also lasts longer (twice as long as a petrol engine, on the average), and requires little maintenance apart from fuel injections and fuel filters. From the viewpoint of energy conservation and better utilization of capital stock, diesel engines look attractive for India. There is little doubt that the extra cost, perhaps 20% above a petrol engine, can be recovered in a very short time. (If a diesel engine were to cost Rs. 3000 more, a car driving 15,000 km/year would recover the cost in 1.5 years, assuming 16 km/l for diesel and 10 km/l for petrol engine.)

C. Energy Savings in Appliances.

There is little doubt that significant savings are possible in home appliances -- air conditioners, refrigerators, etc. In the U.S.,
it is possible to get air conditioners which vary in their energy-efficiency-ratios (BTU out/\text{w-hr. in}) from 5 to 12. Generally speaking, the more efficient units (with higher EER) cost a little more, but the extra cost is offset in a year due to operational savings. Similar considerations apply to India. Consumer awareness of efficiencies is needed, and the government has an important role to play in this area. Requiring manufacturers to label energy consumption of an appliance, along with typical operating costs for different regions, can be instrumental in forcing inefficient units out of the marketplace. If necessary, minimum standards can be required.

D. Energy Savings in Power Generation.

Power generation is second only to industrial use in having large potentials for economical energy savings. Increasing the efficiency of power generation in new units from 31% to 40%, using state-of-the-art technology, seems reasonable. Perhaps, combined-cycle units, using existing Rolls-Royce Aero A-1 jet turbines coupled with existing BHEL steam boilers and turbines, are capable of 44-45% efficiency, if a gaseous fuel is used for gas turbine part of combined-cycle units. (This will be dealt with at greater length in the section on coal utilization.)

The potential for saving coal by using higher efficiency power generation is quite large. The total electricity generation in 1991, after allowing for a saving of $50 \times 10^9 \text{kwh}$, may be $348 \times 10^9 \text{kwh}$. (Ref. 1). Assuming hydropower to contribute $125 \times 10^9 \text{kwh}$ ($28.5 \times 10^9 \text{MW}$) and nuclear to contribute $12 \times 10^9 \text{kwh}$ ($2100 \text{MW}$ -- a much lower growth rate of nuclear power than projected by FPC), leaves $211 \times 10^9 \text{kwh}$ to be produced by coal-fired stations. Assuming that 1/2 of this energy comes from plants installed
after 1980, the saving in coal, using only 38% efficiency (instead of 31%), is 10.5 million tons/year.

V. Status of Research on Energy Conservation in India

The principal agency involved in work on energy conservation in India is the National Productivity Council. P.R. Srinivasan and his colleagues in the Fuel Efficiency Cell of NPC have been working on process modifications in specific industries to reduce energy use, and have also identified possible sites for the application of the total energy concept. They have brought out a number of reports on energy conservation in Indian industry.

Unfortunately, their work has been, by and large, ignored by policy makers. In order to have a significant impact, the efforts at the NPC must be expanded several-fold. In addition, the industry, both private-sector and public-sector, must be made aware of the potential for energy conservation, and should be required to submit detailed analyses of energy conservation strategies and their economic feasibility. India has enough well-trained engineers to be able to handle this task internally. There are also many consulting firms which are capable of doing the studies. Perhaps the leading firms, such as Tata Consulting Engineers, Dastur & Co., and Engineers India should be asked to prepare preliminary studies of a few of the larger industries. This involvement of larger, prestigious firms may act as a catalyst to spur the smaller firms to submit proposals covering the entire spectrum of industries. The government has a very important role to play in this strategy. It can not only compel industries to prepare reports, but can also fund studies, both by private sector and public sector companies, in energy conservation. It seems to me that
this carrot-and-stick approach is preferable to simply requiring studies.

There is also a need for a few economic research institutions to keep an overall view of energy consumption patterns and integrate energy conservation into a growth strategy. Some institutions which may be able to handle this task are the National Council on Applied Economic Research (Delhi), the Operations Research Group (Baroda), the Sardar Patel Institute (Ahmedabad), the Indian Institute of Management (Ahmedabad and Bangalore), Tata Economic Consultancy Service (Bombay), and the Indian Statistical Institute (Delhi).

In addition to studies, of course, there is a need for pilot plants and design innovations. Thus, the Mahindra Group has developed a diesel powered jeep. Perhaps the other automobile manufacturers (Premier Automotives, Hindustan Motors, and Standard Motors) can be induced to develop diesels, perhaps with the help of TELCO, Mahindra & Kirloskar, India is sufficiently advanced in diesel technology that no outside collaboration should be necessary. One form of inducement could be government contracts which could underwrite some of the development costs. This is particularly important for the smaller industries, where new processes may not be developed otherwise because of the almost total absence of R&D. (This absence of industrial R&D has profound implications for India's foreign trade. It almost certainly adversely affects sales to more advanced countries. For example, the absence of multi-speed, light-weight bicycles from Indian manufacturers has almost completely closed off the U.S. and West European market to Indian bicycles.) Not all relevant R&D can be done abroad, nor can it be always imported.
VI. Coal Utilization

Indian coal reserves are mostly concentrated in three adjoining states — Bengal, Bihar, and Madhya Pradesh, though there are substantial deposits in Tamil Nadu, Andhra Pradesh, and Maharashtra. As a result of the well-known transport problems of coal, utilization of outlying coal deposits and conversion of coal into gas and oil become very relevant, along with mine-mouth generation.

As mentioned earlier, one way of utilizing coal efficiently is use to combine-cycle power plants. The principle of combined-cycle power plants is very simple. Gas (or oil) is burnt in an industrial (or jet) gas turbine, which acts as a prime-mover to generate power at 25% efficiency. The exhaust gases from this turbine come out at 600–700°C, and can be used to provide part of the heat needed to generate steam for a steam turbine. The steam turbine could be fired with coal as a primary fuel for the boiler. Again, because of the waste heat utilization from gas turbine, the overall efficiency can be 45%. (Units with 45% efficiency are already commercial in the U.S.) One of the real advantages of combined-cycle plants is the small unit sizes (30–70 MW/unit) even for high efficiency units. Another advantage is a lower capital cost than a coal-fired plant. (Capital costs are typically $250–300/kW, versus $400/kW for a coal-plant.) But, of course, the gas turbine part, at least (and perhaps the steam boiler, too) needs gaseous or liquid fuel, which is more expensive than coal.*

Combined-cycle units may make particular sense for India because nearly 200 Rolls Royce A-1 jet engines are available in the international market for scrap value ($5000 – $10,000 each). Each of these engines can generate about 10 MW, and the technology for servicing these engines is .

*Recently, in the U.S., there is considerable interest in using fluidized-bed coal combustion for firing gas turbines.
available in India. Thus, each of these engines, when coupled with a BHEL 30 MW boiler -- steam turbine, can produce 40 MW. While some modifications will have to be made to the inlet of A-1 engines to fuel them on gas, these modifications along with compression of gas should be able to achieve the necessary flow rates. In any event, the total costs should be very low, considering that the turbine is almost free.

The fuel for these units would have to be gas (or oil). Technology for producing low BTU gas from coal is well known. (It is worth noting that the first step in a coal-based fertilizer plant, which India is building, is low BTU gasification, which gives a mixture of H₂, CO and CH₄). This low-BTU gas is ideally suited for power generation. (Commonwealth Edison in Illinois is building a 75 MW gasifier to feed gas to a 75 MW combined-cycle plant). The gasification stage also knocks out ash and sulfur at the gasification stage, thus eliminating many of the problems with Indian coal. In particular, fluidized bed gasifiers (for example, the Ignifluid design of French Babcock-Wilcox) may be very suitable for certain Indian coals.

There is another advantage of gasification of coal. Low BTU gas provides ideal starting material for certain industrial chemicals, for example, methanol and fertilizers. Thus, the creation of a complex using low BTU gasification for both power generation and chemical production may be very attractive in certain locations. And, of course, gas can be burnt in industries which require a clean fuel, such as chemicals.

Similarly, coal liquefaction may make a lot of sense for India if high thermal efficiencies can be achieved and the cost kept below
Rs $20/10^6$ kJ. (1 kCal = 4.18 kJ, 1 BTU = 1.04 kJ.) This is because oil is easy to transport and also easy to burn. (The typical efficiency of coal-gasification can be 85% for low-BTU gas. Coal liquefaction will almost certainly have lower efficiency, perhaps 70%.)

To give an example of a possible location for outlying coal-utilization, consider Gujarat. The Kutch region of Gujarat has 200 million tons of lignite. This lignite is easy to mine, and may cost Rs. 60/ton to mine, using strip-mining. The cost of Madhya Pradesh coal to neighboring Saurashtra region is Rs. 250/ton. Even allowing for the lower calorific value of lignite, the cost differential is Rs. 150/ton. A million tons of lignite can generate $1.3 \times 10^9$ kWh a year at 38% efficiency (or 220 MW for 6000 hours/year). Yet, today, not one kg of this lignite is being used, and Gujarat is totally dependent upon rail transport for coal, over two different railway gauges (Broad and Meter Gauges are used in different parts of India.)

It is also possible that Gujarat lignite can be used for supplying a gasifier to produce low-BTU gas. Whether or not this is feasible will depend to a large extent on the availability of sufficient water of the right quality for the gasification process. The Kutch region may be scarce in water; but neighboring regions of South Gujarat, or around Bombay, adequate water for gasification. Locating a gasifier in these regions may make economic sense, because of the concentration of industry in these locations.

In any event, the use of lignite deposits in Kutch, for either direct power generation, or for producing low BTU gas, and then using this gas for a multi-purpose plant (generation of electricity and use of gas as either feedstock for fertilizers or methanol, or as heating stock for industrial processes) deserves careful and immediate study.
VII. Status of R&D on Coal Utilization

The principal institution involved in research on coal utilization and conversion, of course, is the Fuel Research Institute at Dhanbad. A number of pilot plants have been built at Dhanbad, among them gasifiers, fluidized-bed combustors and hydrogenation plants for coal liquefaction. There is little doubt that India has the technical manpower to tackle coal conversion and utilization problems. But, so far, this manpower and knowledge have not been utilized by the policy-makers. Recommendations for coal gasification have been made for over 20 years, and have been ignored. In the days when oil was $1.80/barrel, perhaps this made sense. But since 1973, the need for intensive coal-conversion efforts has been very clear.

Perhaps one strategy for accelerating coal utilization and conversion in India would be to engage in large-scale pilot-plant testing of Indian coal outside of India. The existing gasifiers in the U.K., West Germany, France and the U.S. should be utilized to test reactions of different grades of Indian coal on a large scale. In this way, the remaining technological uncertainties can be removed, and a suitable design found rapidly. Then, BHEL or CFRI can enter into technical collaboration and manufacture these units in India. (This is not meant as a reflection on the excellent work of CFRI. It is only suggested as a short-cut to get around the years of neglect shown to the work of CFRI.) India should not have any difficulty in finding suitable and willing partners in this venture.
VIII. Solar Energy

Most of India is blessed with direct sunshine at least nine months a year. Parts of India, such as northern Gujarat and southern and western Rajasthan, have almost 330 days of direct sunshine every year. The average solar insolation in India is around 2500 kwh/m²-year. In places like Rajasthan and Gujarat the average insolation is 3000 kwh/m²-year. Thus, 5 m² of India receive as much energy in a year from the sun as is contained in one ton of oil. Clearly, solar energy is a very important resource for India. Its greatest virtues are its reliability for most of the year (except the monsoon months) and its uniformity across the land. The pattern of solar energy distribution is fairly similar over most of India, with only the Himalayan region (Kashmir) having a low incidence of sunshine on the ground.

The Government of India, recognizing the importance of solar energy, set up a panel under National Committee on Science and Technology to look into the prospects for utilization of solar energy in India. This panel submitted a report in 1974, and the interested reader is referred to that report for some useful background information.

Before proceeding with a detailed discussion of solar energy, it is important to note that solar energy is being used in India to a very large extent. Most of the fuels used in rural areas, and in hydroelectricity, are derived from solar energy. In addition, most of the fuels used in rural areas (firewood, cow dung, vegetable waste) are "free" to the user, though not zero-cost to the society. The very severe deforestation of India due to extensive felling of firewood has profound implications for the future of India. There is no doubt that, in some cases, deforestation had led to
man-made deserts. Gujarat is almost a classic case in point. Deforestation reduces the permeability of the soil to moisture and increases soil erosion and floods. It may also have adverse climatic effects. The severe erosion in the Himalayas caused by deforestation has already led to a rapid siltation of the major dams, such as Bhakra-Nangal. Therefore, the provision of a low cost, or a zero-private-cost, energy for the rural population is a critical problem for India and the solution will have to come from utilizing 'current' solar energy, one way or the other.
IX. Methods of Utilizing Solar Energy

There are three major ways of utilizing solar energy:

1. Production of Fuels. Here, solar energy can be converted into fuels such as methane or hydrogen, or hydrocarbons (through photosynthesis).

2. Use of solar heat. Solar heat can be used for such purposes as drying of crops, heating of water and buildings, refrigeration and air-conditioning, distillation of water for provision of drinking water, high efficiency biogasification, and production of steam to drive engines or pumps.

3. Production of electricity. Electricity can be produced using either using solar cells, or by driving turbine/solar-heated steam, or by helio-hydroelectric schemes, or by exploiting ocean-thermal temperature gradients.

I shall discuss each of these, and show their promises and problems for India.

1. Production of Fuels:

There are many ways of producing fuel using solar energy.

A. Photolysis of water. The photons in solar energy incident on the earth have a wide energy distribution, with the highest energy photons having energy of 3 eV. The peak number of photons is at around 2 eV. The energy required for producing H₂ and O₂ is 1.23 eV per molecule of water. Consequently, it should be possible to use a material which converts the higher energy solar photons into electrons, and these can be transferred to the radical (H⁺) to produce H₂. Hydrogen, of course, is an excellent fuel. There are many interesting experiments being done in the U.S. and Japan using powdered semi-conductors, and also using surface catalytic action of Ni. The initial results show that H₂ is indeed generated, but the
experiments are really in a very preliminary stage. Therefore, the application of this technology to India must await technological feasibility.

B. Photosynthesis. Photosynthesis is a very practical process, and the only question is whether it is possible to harness it economically for large scale production of fuels in a land scarce country such as India.

There are many ways of utilizing photosynthesis. The highest efficiency for converting solar energy into hydrocarbons is achieved by certain algae. However, these algae require water ponds, and water is scarce in India. Perhaps the easiest and most practical way of converting solar energy to hydrocarbons is to use fast growing trees. We know that certain species, such as eucalyptus, are very fast growing, and therefore have high photosynthetic efficiency (0.5% - 1%). We also know that eucalyptus plantations have become quite common in India in the last two decades. We also know that for drier areas, "neem" and Babul" trees are also fast growing. Recent experiments in India suggest that when some of the more common brush-type trees are cut and new columns grafted onto them, the brush tree instead grows into a regular tree, and quite rapidly too. There are probably many other Indian trees which achieve maturity in 4-8 years. Therefore, if some of these trees can be grown in an energy plantation, such plantations may provide ready source of fuel for village use. Note, of course, that the environmental benefits are outstanding. Among these are reduction of soil erosion, reduction in floods and the possibility of providing fodder to village cattle. It is important to note that, in some cases, it is possible to grow grass between lines of trees. The author has seen an experiment near Ahmedabad, where an innovative farmer, on his own, experimented with a 60 hectare eucalyptus plantation, achieving full growth (10-15 M height)
in four years. This farmer also experimented with planting grass between eucalyptus rows and succeeded in achieving a high yield of a couple of varieties of grass, one being Guinea Grass.

It is interesting to consider the potential of these village woodlots, or "social forestry" as it is known in India. A village of 500 people (100 households) needs approximately $0.6 \times 10^6$ kWh/year for cooking, using low efficiency stoves. Using 0.5% photosynthetic efficiency, this energy could be provided by a village woodlot of 4.8 hectares -- a small area indeed. (The investment cost for this plantation may be Rs. 20,000).

Of course, if the efficiency of the stove can be improved to 40-50%, the energy consumption drops significantly.

Note that so far we have talked about low efficiency trees. But, as the experience in the U.S. indicates, it is possible to achieve a "green revolution" in trees, by developing high yield forestry, using genetic manipulations. Certainly, selecting fast growing, high yield trees and selective breeding of new varieties must become a prime area of research in India.

It is possible that trees such as eucalyptus and bamboo may provide a partial answer to increasing water tables in canal-fed areas. It is possible that the ability of eucalyptus and bamboo to transpire large quantities of water can be used to control water tables and salinity levels faced by crops.

Note that in certain locations, it is possible to grow large scale plantations of trees to provide wood for power stations. The investment costs for such plantations are claimed to be lower than the investments in coal mines and railroads. But the question of using
large land areas for fuel generation for power stations instead of growing food has to be addressed.

C. Biogasification of Organic Waste. This subject is treated extensively in a separate chapter.

2. Use of Solar Heat

A. Hot water heaters. Hot water heaters, using flat-plate collectors, are well known devices. India has been working on these for at least 20 years. The technology is simple, and a 50 litre unit may cost Rs. 500-Rs. 1000. Thus, the solar water heater is well within the economic range of the urban population. A typical collector is shown in Figure 1. The application of this technology to rural India is marginal. It is unlikely that a typical villager is interested in spending a large part of his annual income on a luxury like solar water heater, either for hot water use or for space heating in winter time. Solar water heater must be regarded as a luxury item in India.

However, there is one important application of solar water heating for India. This is for industrial water heating. Chemicals, textiles, etc., use steam for processing, and using simple concentrators, it is possible to provide low pressure steam at 100-120°C for industrial processing. Alternatively, solar energy can be used to preheat water going into a steam boiler.

B. Solar space heating. As mentioned earlier, solar space conditioning using hot water is impractical for rural India. But, it should be possible to incorporate solar heat in a simple way to heat buildings, or village huts. Particularly, where metal roofs are used, or brick walls, solar
Operation: Light comes in through the glass cover, and is absorbed by the black metal plate; the heat is transmitted to the water flowing through the pipes. The water is collected in a tank. The glass plate keeps the heat in by preventing conductive and radiative heat transfer, and the insulation at the bottom serves the same purpose.

Figure 1

A Typical Solar Collector
heating is easy. A simple design would consist of painting the south-facing wall black, and then creating a dead air-space by putting a transparent sheet of plastic, separated from the wall by spacers. The sun will heat up the bricks, and the dead-space will prevent convection of this heat. At night, the plastic can be covered with an insulating cloth to prevent radiation loss. A similar design can be used on the metal roof, where a layer of water may act as a storing agent. A schematic diagram of this system is shown in Figure 3.

C. Solar air-conditioning. Again, this must be regarded as a luxury. Nevertheless, air conditioning demand in cities is growing, and there are a variety of ways in which solar energy can be used for air-conditioning.

Perhaps the simplest is a sky-therm type of air-conditioning. The principle is very simple. Consider a building with a roof made out of a material which is a good conductor of heat. If we enclose a layer of water on this roof and cover it from the sun during the daytime, the water will absorb heat from the house. At night, we can remove the cover, and the water will radiate heat to the sky and cool down. It is also possible to use evaporation of water during night-time to further cool the house. During the day, the roof is again protected against the sun, and the cycle repeats. There is no reason why this system cannot work in India, provided house designs are changed slightly. A diagram of the system is shown in Figure 4.

A more involved system for air-conditioning uses the familiar absorption-refrigeration cycle, used in India in the "Electrolux" type refrigerators (which run on kerosene or gas). Solar energy can be used to provide heat to vaporize ammonia, which is the working fluid in the unit.
Figure 2

A Simple Space Heating System

The south side of the house can be painted black, and a plastic sheet can be laid on it, separated by a dead air space. During the day, the brick wall will absorb the heat of the sun, and heat up, and the plastic will prevent infrared radiation out and also prevent convective heat transfer. At night, the plastic can be covered with a simple reflecting cover, which will minimize radiant heat transfer. The brick wall will act like heat storage, and convect and radiate heat into the house.
Figure 3
D. Solar refrigeration. Unlike air conditioning, solar refrigeration has important economic applications. Among these are preservation of agricultural produce such as vegetables, fruits, milk and pulses. For example, about 50% of the milk which reaches Amul Dairy in Anand is sour in the summer months -- a tremendous economic waste. A solar powered refrigerator may, for example, make ice blocks which can then be used to preserve these perishable produce.

E. Solar distillation. The heat of the sun can be used to increase the temperature, and consequently, vapor pressure of water, which will then evaporate, producing distilled water. India has been working on solar stills for quite a few years. Solar stills have an important application because in many parts of India, there is not enough drinking water during drought years. During the 1974 drought, for example, water had to be carried by tankers to many villages in Maharashtra and Gujarat, at an enormous cost to the nation. (Perhaps Rs. 10-20 per 1000 liters). Since brackish water (or sea water) is often available in these areas, solar distillation can provide an important technology for providing drinking water, even at the high cost of Rs. 2-4/1000 liters. A typical solar still is shown in Figure 4.

F. Solar drying of crops. The heat of the sun can be used to produce high temperatures (60-80°C) in an enclosed area. Therefore, such dry hot-boxes may be useful in the drying of certain crops where laying them on the ground can lead to contamination with dirt or attack by insects. Among such applications may be the production of dried fruit, drying of tea leaves, drying of lumber, etc.
Figure 4

Solar Distillation

In this arrangement, solar energy is used to heat up and increase the vapor pressure of brackish water in the black trough. The vapors condense at the cooler roof, and due to surface tension, trickle down the side of the roof into a collecting trough. The tilting mirrors can be used to increase the collecting area for sunlight, increasing the temperature of the water, and therefore increasing the yield per day.
G. Solar cooker. India of course, has been working on solar cookers for a number of years. Again, the principle is very simple. A set of mirrors focuses the rays of the sun inside a closed box with a black interior, which absorbs the heat. Since the box is closed, the concentration factor can bring the temperature inside to 150-175°C, adequate for cooking vegetables and rice and pulses. The cooker is quite cheap, Rs. 150-200, and is quite within the economic reach of the urban population, and the upper level of the village population. Two meals a day can be cooked in it, but "chapati" (Indian bread) cannot be cooked because it requires high temperatures. Unfortunately, the cooker presents a problem in urban areas since the cooking has to be done outside.

H. Solar pumps. Perhaps the most important application of solar energy in India is for irrigation. As explained earlier, solar energy is almost perfectly suited for irrigation, since storage problems are minimal in irrigation, and the major use of irrigation is for the winter crop, when the sun shines just about every day.

One simple technology which has caught the interest of many people in India is a solar pump. The principle is very simple. Solar heat can be used to generate a vapor from a low boiling point liquid such as pentane or methyl chloride. This vapor can then act as a liquid piston to push up water to a tank. When the vapor condenses, a partial vacuum is created, which sucks up water from the well. If a high enough temperature can be reached, steam can also be generated, which can run a steam engine. A diagram of one such vapor pump is shown in Figure 6.

However, there are problems with this technology. The major problem lies in the low thermodynamic efficiency for converting heat into work. The low temperatures that can be achieved by flat plate collectors
Operation: Solar heat generates steam under pressure. This steam pushes water up to the tank. The steam gets cooled in the condenser, the pressure reduces, and water is sucked in through the suction pipe, and the cycle is ready to repeat. The two one-way valves keep water from flowing back.

Figure 5
Vapour-Pulse Engine

(Source: Dr. Kuppa Rao, Indian Institute of Science)
are the major problem. Thermodynamic efficiency is given by $\eta = \frac{T_1 - T_0}{T_1}$, where $T_1$ is the temperature of the heat source and $T_0$ of the sink. Typically, $T_1 - T_0 = 40-50^\circ K$, and $T_1 = 360^\circ K$, hence, $\eta \approx 14\%$, which means that real-life efficiency will be 5-6%. This low efficiency means very large structures for a given power output, which in turn means high cost per kW. An optimistic cost estimate for such pumps is Rs. 15000/kW. But, considering that this estimate depended on reaching a temperature of 90°C, for which some form of concentration will be needed, the cost estimate seems low.

Note also that the solar pump can only pump water. It cannot do anything else.

In my opinion, the development of cost effective solar pump depends crucially upon the achievement of high temperatures (200°C) to achieve a higher thermodynamic efficiency. The solar pump may be "simple," but it is not cost effective, and present versions are not particularly appropriate from an economic viewpoint.

3. Solar-electrification

Solar-electrification is a well known technology. The problem, until recently, has been the very high cost of direct power generation (Rs. 100,000/kW). But, recently, many interesting developments have occurred which promise to reduce this cost drastically in the very near future (2-3 years).

A. Solar-thermal-electric. The simplest way of generating electricity using solar energy is to use the heat of the sun. By collecting heat in flat-plate collectors and using a low vapor pressure fluid, we can create hot vapor which will drive a turbine. Methyl chloride, refrigerants (freon) and ammonia are some suitable liquids. But, the low thermodynamic
efficiency of flat plate collectors presents severe cost constraints, and costs are unlikely to be below Rs. 20,000-50,000/kW for low pressure solar turbines.

However, there is no reason to be limited to low temperatures for steam generation. It is well known that by focusing heat on a spot by mirrors, high temperatures can be achieved. The French have a solar furnace working in the Pyrenees, producing temperatures of over 2000°C, using parabolic reflectors. Similarly, for power generation, we can focus the rays of the sun on a tower top, about 100 M high, using mirrors on the grounds. The mirrors track the sun as it moves from east to west. The concept is exceedingly simple, and uses technology components which are widely available in India, or can be made easily. By focusing heat on a boiler placed atop the tower, temperatures of 400°C-500°C can be reached easily. (The boiler, of course, will be coated with a paint with a higher index of absorption to emission, and will be surrounded by a transparent dead-space to minimize convection losses.) At this temperature, 33% efficiency power generation can be easily achieved, using existing BHEL steam turbines. Even allowing for only 75% collection efficiency of sunlight, and 10% heat loss, an overall solar-electric efficiency of 20% should be easily obtained. Sandia Laboratories in the U.S. is building a prototype (1MW) model of this "solar-tower-power" concept, and indications are that a 10 MW power plant should be in operation in the U.S. by 1980. The cost estimates are ~ $1000/kW.

The regions of India where this scheme can be most economical are the arid regions of western India (Kutch, northern Gujarat, western and southern Rajasthan) where the sun shines brightly over 300 days a year, and in some places over 330 days a year. Thus, 3000 hours of sunlight

* Solar Tower is shown in Figure 6.
are available for power generation in these regions, and shortage problems are minimized because of the very few cloudy days.

Over night storage, of course, should be provided for an efficient, integrated system. The easiest way of providing storage is to use pumped-storage plants. In a pumped-storage plant, water is pumped uphill when power is available, and this water flows downhill, regenerating power, when power is needed by the system. India is already building three large pumped-storage plants, one of which is located on the Gujarat-Rajasthan border, and can be used to provide storage for several solar power stations. In any event, the volumes of water needed for storing energy are quite small. For example, for storing 100 MW of energy for 16 hours, we need two reservoirs, each of \( \approx 20 \) hectares and 10 M deep, one at the bottom of a mountain, and the other on top, with the head being \( \approx 300 \) M.

This ease of storage is one of the virtues of solar electrification over solar pumps. It is far harder to store large amounts of heat efficiently than to store electricity.

Schematic diagrams of a solar power station and a pumped-storage plant are shown in Figure 7 and Figure 8 respectively.

Note that the active area required for a solar power station of 1 MW is 5000 m\(^2\) at 20% efficiency. Allowing for space between rows of mirrors gives an area of \( \approx 10,000 \) m\(^2\)/MW; (1 ha/MW) -- a very small area indeed.

In my opinion, it is essential that India start work on a prototype 100 kW solar station of this type. Only by doing actual experiments can we find out the real problems and promises of the technique. The
Operation: The field of mirrors track the sun and focus energy on the boiler, producing steam at high temperature (500°C). The steam then drives a turbine. The boiler is kept hot by vacuum lining and also by using appropriate optical coatings on the boiler.

Figure 6

Solar Thermal-Electric System
Operation: During the period when the load on the system is low, the water is pumped uphill using reversible pump-turbines. During periods of high demand, water flows downhill and generates power. Such a system can be used to store solar energy.

Figure 7

Pumped Storage Plant.
costs may lie in the range of Rs. 10,000/kW-20,000/kW for the prototype. In any event, a study of the costs involved is absolutely essential.

B. Direct conversion (solar photovoltaic)

Solar cells have been a well-known technology, and have been used to provide power for satellites. Until recently, the costs were high, but recent developments have changed the picture significantly.

The principle of the solar cell is very simple. Photons shining on a semiconductor can generate electrons, and these electrons can be collected, giving rise to a current at a voltage which depends on the semiconductor. A semiconductor solar cell is one of the simplest semiconductor devices. Typical conversion efficiencies are 15-20%.

The reason for the high cost of these devices (Rs. 100,000/kW) lies in the cost of the semiconducting material itself. High purity silicon, the most basic semiconductor material, costs Rs. 500/kg in polycrystalline form, and Rs. 2000-3000/kg in single crystal form. A good single crystal silicon solar cell requires about 0.1 gm/cm², or about Rs. 20,000/kW in material cost alone. Hence, it is difficult to make single crystal solar cells for less than Rs. 50,000/kW.

If, on the other hand, polycrystalline or amorphous materials could be developed to give 10% efficiency, costs can be reduced, because certain materials, such as GaAs and CdTe and even polycrystalline silicon, require only about 10⁻³ cm thick layers. The cost of the material (silicon) then drops to Rs. 125/kW, and it is then feasible to make cheap solar cells directly. There is intensive research going on to make polycrystalline solar cells with reasonable efficiencies (5-10%) and long field lives (20 years). But, thus far, no proven technology is available which can deliver these solar cells.
There is a simple way to make cheap solar cells today. The principle is very simple. Since solar cells depend on electron generation by photons, the more photons there are, the more electrons we get. If we focus light on existing solar cells, say by a factor of 100, using either lenses or parabolic reflectors, we can get 100 times more power from existing solar cells, and we have effectively reduced cost by a factor of 100. Thus, Silicon solar cells of today would be reduced in cost to Rs. 1000/kW. Of course, we have to add on the cost of concentrators and of means for tracking the sun. But these costs are low compared to the cost of Silicon. For example, a plastic lens array is only expected to cost Rs. 1000/kW. The total system costs are expected to be below Rs. 5000/kW.

Tracking can be either completely automated with a fractional kW motor and a large gear ratio, or a parabolic cylinder reflector can be laid along East-West axis, and the cylinder can track the sun manually every 15-20 minutes using a simple gear arrangement. (This latter method is particularly suited to India.) The principle of these "high-intensity" solar cells is shown in Figure 8, and a parabolic trough reflector with manual tracking is shown in Figure 9.

These high-intensity solar cells have been made, tested and proven in the U.S. in the last two years. Their great virtue is that they use state-of-the-art technology, with no breakthroughs required. A photograph of an operating 100W prototype model is shown in Figure 11. There is no doubt that India already has the technology to build these solar cell arrays.
Another virtue of solar-cell power is the small unit size. The economy of scale comes not in building a 10 kW plant, but in building many small 1 kW plants. When we remember that the typical irrigation pumps in India are 1-10 kW size, the applicability of the scheme for irrigation is obvious. Irrigation requires no storage, apart from a lead acid battery to provide starting torque (typical cost ~ Rs. 200) for the pump.

Note also that a solar-cell array can be used for purposes other than irrigation. Thus, a lead-acid battery, particularly the "dry" type recently introduced in the U.S. market, can be charged up for example, for two hours every day by a farmer's solar-cell array. Then, this battery can be carried home to provide a four hour output to light the farmer's home, or to provide electricity for the village educational TV set, etc. During the months when irrigation is not necessary, solar cells can be used to power small-scale village industry. Thus, a higher utilization of capital is possible using electricity generation than in the case of solar pumps, which lie idle when water is not necessary. Electricity is the best kind of energy to generate. It can do anything from then on, ranging from heat production to motive power, all with close to 90-95% efficiency.

In my opinion, building prototype 1 kW arrays of these high-intensity solar cells should be a very high priority strategy for India. Only by building prototypes, and testing them under actual field conditions, powering an irrigation pump with them, can we know what the best tracking system is, what the effects of dust storms are, etc. Paper studies are not likely to answer these questions.
Operation: Sunlight is concentrated by the lens on a small area solar cell. The solar cell produces electric power. The heat is dissipated by the heat sink. The entire mechanism tracks the sun using appropriate gears, etc. Since the area of the solar cell is kept small, the cost is low. (A given area of the solar cell produces more power than would be the case without any focusing.)

Figure 8

High Intensity Solar Cell
Figure 9

Sun

Parabolic Trough

Solar Cells (linear array)
Fig 11

Non-Tracking CPC

Winston Collector
(Incidentally, recently, a very promising non-tracking collector which can focus by a factor of 10 has been designed, built and tested in the U.S. It uses ingenious optics, consisting of two parabolic reflectors inclined at an angle to the optic axis of the conical-trough like device, to collect even scattered sunlight. Again, a simple, occasional, manual tracking can be used to optimize these "Winston" collectors. Figure II shows this collector.)

C. Heliodydroelectric. The principle of this scheme is again very simple. Consider a long, narrow body of water (e.g., the Red Sea). If this body of water lies in an arid, hot area, the evaporation rate of water is quite high (3M/year), if this water were isolated from the cooling effect of the ocean. Thus, if we create a "dead" sea by damming such a narrow bay, in 3-4 years, we should have a head of 10M, and we can run low-head hydroelectric turbines across the dam, generating power.

The area in India suitable for such a scheme is the little Rann of Kutch, which is a "desert" sea. By damming the narrow neck a little east of Kandla Port, perhaps 50 MW can be generated.

Note that the environmental consequences in certain locations could be quite severe. They are likely to be extremely severe for the Red Sea, since the Red Sea is quite deep and supports many species of marine life. Rann of Kutch is probably a much better location from the point of view of environmental consequences than the Red Sea, but studies ought to be done before undertaking any such scheme.

There may be a side benefit of this heliodydroelectric scheme. The increased salinity levels in a dead sea may provide some important chemicals and salts more economically than directly from sea water. But
Fig. 1. Profile curve of ideal collector. The axis of the parabola is inclined at angle \( \theta_m \) to the optic axis (OA).

Fig. 2. Trough-shaped cylindrical collector. Reflective vertical end walls make collector appear optically infinitely long.
many more studies need to be done before a final design can be evolved.

D. Ocean-thermal electric. This scheme relies on utilizing the temperature differential between the top and bottom layers of a tropical ocean. The top layers are 10-15°C warmer than the underlying layers and, in principle, a turbine can be run between these layers, using a low boiling point fluid. But, in reality, the efficiencies are so low (2-3%), and the problems of corrosion etc., so severe, that this scheme belongs more to science fiction than fact.

E. Solar satellite power system. The idea here is to put up a huge satellite in synchronous orbit around the earth, and convert solar energy to electricity in space, and then transmit it to earth using microwaves. The basic motivation is avoiding the storage problem, since in synchronous orbit at 40,000 km out in space, sun will shine for 22.5 hours a day. The idea is totally ridiculous, since storage is not that much a problem on earth, and even more efficient storage means (flywheels, batteries) will be developed long before a huge satellite array of 5 km x 5 km can be put up in space. The economics are extremely dubious and this is truly a science fiction scheme with no relevance to India (or even the U.S. for that matter).
X. **Status of Research in India on Solar Energy**

1. **Fuel Production**

   A. **Photolysis.** There is almost no work being done in India on direct photolysis of water. Perhaps the National Physical Laboratory in New Delhi, or the National Chemical Laboratory in Poona, are the two best laboratories to start work on photolysis. Each of these have the critical mass of scientists, so that a productive research effort can be carried out. However, photolysis is in such an early state of R&D even in the U.S. and elsewhere that a large effort in India would not be warranted.

   B. **Photosynthesis.** India is quite advanced in forestry research. The Forest Research Institute in Dehradun is one of the leading forestry institutes in the world. The forestry departments of the different states are also well staffed with many highly competent scientists. Thus, India has a critical mass both in manpower and experience in forestry. There is no reason why India cannot embark on an ambitious, large scale program of village woodlots if the financial resources can be made available.

   This is not to say that research is not needed. High yield forestry with new species of trees, much like the green revolution in agriculture, is a fairly recent development, and probably a great deal of work needs to be done on breeding the best species of trees for the very diverse climates of different parts of India. Funding may be a problem here, but again, manpower seems adequate and highly competent, and also, strongly motivated.

   As far as algal cultures are concerned, only ITT, Kanpur, seems to be actively involved in this work on a scientific basis. Algae may hold the potential for a real breakthrough in solar photosynthesis,
but it is beyond my competence to make any judgements in this field.

2. Solar Thermal Systems

A. Hot water heaters. India is quite advanced in the field of hot water heating using solar energy. The leading institutes are Arid Zone Research Lab. in Jodhpur, Building Design Research Institute in Roorkee, NPL in Delhi, and Salt & Marine Chemicals Research Institute in Bhavnagar among the public sector institutes. Among the private sector companies, the leading institutes are Jyoti Ltd. in Baroda, and Kapur Solar Farms in Delhi.

Solar water heating is a fairly mature technology as far as conventional R&D goes. There are very few new ideas in the field. Perhaps the most innovative research in India in this field is being done by Jyoti Ltd. (out of their own funds). They have recognized the limitations of low temperature heating for either motive power or industrial use, and are developing a simple concentrator for producing 150-200°C water. Kapur Solar Farms are working on eutectic salt storage of heat. Frankly, I am dubious about eutectic salt heat storage. So far, the experience in the U.S. has been very poor with eutectic salts, and long cycle lives have been hard to achieve. In any event, water is such a good storage medium for heat that it is hard to see any major application of salts for storage of heat in India.

Bharat Heavy Electricals Ltd. (BHEL) have been appointed project managers for solar thermal systems by the Department of Science and Technology. Many of the research and demonstration plants are being funded through them.
The leading areas needing research, in my opinion are: simple solar concentrators, low-cost and long-life collectors and cheap, efficient heat-transfer mediums.

In particular, I do not see how a flat plate collector with galvanized iron tubings carrying water will ever be a low cost, high efficiency collector. Thermal efficiencies are much better with a sandwich collector, consisting of two galvanized iron plates, with water between them. This method is also cheaper. Development of low cost, good conduction plastic tubings, or enhancement of absorption of water itself, may provide even lower costs.

and Fresnel lenses

Similarly, parabolic reflectors seem to hold a great promise for non-tracking concentrators.

Again, India is fortunate in having such a large mass of highly-trained, very competent scientists in this field. The critical mass exists, and what is needed is a better direction of R&D. There are too many sub-critical, undirected, confused research efforts, often rediscovering the wheel.

B. Space-conditioning (heating and cooling). As explained earlier, almost no work is being done to evolve a suitable, very-low-cost heating system for village use. The skytherm system is likely to be far too expensive, and hot water or hot-air-heating systems, prohibitively so. The Indian Institute of Science at Bangalore, as part of its ASTRA programme, is working on rural housing, and perhaps may be best suited to tackle low-cost solar heating for common villagers. India has a very large body of extremely competent civil engineers, both within and outside the government. There is no reason why a well-directed effort cannot succeed in solving this problem.
Work on solar air-conditioning is proceeding at IIS (Bangalore) and at Roorkee on the sky-therm system. Air conditioning (and refrigeration) units using ammonia are being developed at University of Roorkee and Mechanical Engineering Research Institute at Durgapur. Jyoti Ltd., is also working on refrigeration units.

C. Solar distillation. The leading institutes are Marine Research Lab. at Bhavnagar and AZRL at Jodhpur. Both of these have a great deal of experience in solar distillation. The scientific talents exist, and in large enough numbers for success. However, many more pilot plants employing unusual designs (perhaps use of mirrors, utilizing the arrangements of solar cookers, etc.) should be built before an optimum design can be evolved. Again, there should be a commitment by authorities to support large scale, demonstration testing at several leading places.

D. Crop drying. The leading institutes are AZRL (Jodhpur) and FRI (Dehradun). IIT (Kanpur) and Auroville Institute (Pondicherry) have also worked on solar drying of crops.

The strength, again, is the availability of talent. The weakness is sub-critical support.

E. Solar cookers. India is probably more advanced in the field of solar cookers than any other country. NPL (Delhi) developed one of the earliest solar cookers, though the design was crude and somewhat unsuitable for large pots. But recently, private industry has entered the field, recognizing the potential, and has come up with a much better design, which allows large pots to be placed inside the box. This cooker is a low-attention device, needing tracking only every 15 minutes or so, quite feasible in India for an average housewife. Perhaps the prime need
is for lower cost materials, and some useful work can be done in this field. The applicability can be very great, except in cities, if the costs can be reduced to Rs. 50-100 level from the present Rs. 200.

F. Solar Pumps. This, of course, is a favored technology in India, and is consequently receiving much funding. The leading institutes are Birla Institute of Technology in Pilani, IIT (Madras), Jyoti Ltd., (Baroda), IIS (Bangalore). Most people consider it an "appropriate" technology because it is "simple." As explained earlier, however, it has problems, unless higher temperatures can be developed. Jyoti Ltd. is the only place working on high temperature solar pumps using steam engines.

3. Solar Electrification

A. Solar thermal-electric. The work in this area in India is mainly conducted at BHEL in Delhi, where they are developing a low pressure turbine to run on low boiling point fluids (methyl chloride). As explained earlier, I do not consider this a very viable technology unless 200°C can be developed. Jyoti Ltd. is working on thermal electric systems, using higher temperatures, running a steam engine with 200°C steam.

There is no work being done on the really promising thermal electric system — high temperature (500-600°C) solar towers. This is really very surprising. The Physical Research Laboratories in Ahmedabad is interested in this concept, and they may begin work on this scheme. They are probably the best laboratory to work on this scheme, because of their expertise with radio-telescopes and tracking systems for space research. They obviously have the critical mass, both in talent and numbers, and they also seem to have the enthusiasm so necessary to make things work. They also are ideally located geographically, being near to
the area (northern Gujarat, southern Rajasthan) which seems most promising for a solar-thermal-electric system. In terms of location, the area around Palampur in Gujarat may be ideal for a prototype, since it is already connected to a grid, near enough to a small pumped-storage scheme (Dauniwada), and also near enough to a major industrial center (Ahmedabad). In any event, some suitable location should be selected and a prototype 100 kW plant built. (Note that availability of a suitable hill may make mirror placements a lot easier).

B. Solar photovoltaic (Solar Cells). There is a great deal of work being done in India on direct conversion of solar energy into electricity using photovoltaic conversion (semi-conductor solar cells). Solar cells have been built in India for the last 10 years. The government has established Central Electronics Ltd. in Delhi as the project manager for solar cell work in India.

The leading institutes in India, with a large enough body of scientists in-house to make an impact on the development of a commercial system, are NEL in Delhi, Solid State Physics Laboratory (Delhi), Central Electronics Research Institute (CEERI) in Pilani, Rajasthan and Tata Institute of Fundamental Research in Bombay. Each of these has been involved in semi-conductor work for a considerable time, and each has a large body of very talented scientists. There are many other smaller institutions also in the field. The more notable among these are IIT (Delhi) and IIT (Kanpur).

In this field, as in most others, the research efforts seem too small at any one place to make an impact. Perhaps the most striking observation is the almost complete absence of research efforts on the
part of industry. The leading semi-conductor industry in India is Bharat Electronics Ltd., in Bangalore, who are reputed to have a very modern production line, and even manufacture their own Silicon crystals (unlike others, who have to import). But they do not seem interested in Silicon solar cell work, even though they probably can manufacture solar cells better than anyone else. They also will not sell Silicon crystals to anybody else, not even to national laboratories. Everybody else has either to learn how to make Si, or import. (In the U.S., in contrast, private firms sell to one another, and are often forced to sell by anti-trust laws.) Perhpas it would be a good strategy for BEL to make SI for solar cells, and sell it to others, since it is much easier to increase production at one place than to set up a new plant with its own learning curve.

The other public sector firm, Electronics Corporation of India in Hyderabad, is working on SI solar cells, although, of course, they also import Silicon.

As explained earlier, there is no doubt that a high intensity Silicon solar cell will achieve costs below Rs. 10,000/kW, and most probably, below Rs. 5000/kW. The leading institute in India in this field is CEERI at Pilani. They are designing concentrators and tracking systems, and are also experimenting with high efficiency Si solar cells to work at 100X and 1000X concentrations. They are also very enthusiastic, and seem committed to making things work.

There is some work in India on polycrystalline materials. The leading institutes are NPL (Delhi) and IIT (Delhi). IIT (Kanpur) is working on a novel Silicon solar cell.
Since this is my special field of expertise, I have included an appendix (Appendix A) on what may work in solar cells, and who seems best equipped to work on any given approach.

The present thinking in India seems to be to encourage all solar cell approaches equally. The goal is to produce 100 W panel by 1981. That goal is too modest. I firmly believe that a well-directed effort can produce a 1kW panel, using concentrators, next year. Only by using a 1kW generator with a battery and an irrigation pump in a place like CEERI (Pilani) can the feasibility of the idea of high intensity solar cells be tested. When a very promising and probably cost-effective technology appears on the scene, and is demonstrated to have worked, its feasibility in India should be tested without delay.
XI. Biogasification

Perhaps no other technology is as suitable for India as biogasification of organic waste. Both crop residues and cattle manure can be converted into a gas containing 60% methane, using anaerobic fermentation in a digester. The feasibility of this process is clearly established. Over 20,000 "gobar gas" plants, running primarily on cattle manure, but also using human and agricultural waste in certain locations, have been built in India in the last 20 years. But, the economic feasibility of these plants, at the village level, is not clear, nor are the present plants particularly efficient or cost-effective. Typical energy efficiencies for conversion of cow manure into gas are less than 30% in existing plants.

It is best to start off with an exercise illustrating the potential of biogasification. This is done in Table IV, which suggests that the potential for biogasification is very large indeed. It is important to note that we have assumed a conservative gas yield of 400 l/kg of dry manure. Actual field experiments in India and the U.S. indicate yields of 500-550 l/kg in well stirred biogas plants in which the temperature is kept around 35°C. As indicated earlier, the present-day production plants in India are very inefficient, producing an average of 500-1000 kCal/Kg (100-200 l/kg) especially in colder regions.

It is also important to note that biogas plants produce organic fertilizer in the form of sludge. Dry manure contains about 1.5% of N by weight, 0.5% P, and 1.8% K. Looking at N alone, the cattle in the hypothetical village will produce 4.1 t of N per year, or 27 kg/irrigated hectare. Considering that HYV wheat crop uses 40-60 kg/ha of N per year,
the fertilizer in the biogas sludge can provide about 45%-75% of the Nitrogen needed by the crop.

Table IV

Potential of Biogas in India

<table>
<thead>
<tr>
<th>Description</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 kg of dry manure</td>
<td>400 kCal/kg</td>
</tr>
<tr>
<td>At 55% efficiency</td>
<td>2200 kCal/kg (400 l/kg)</td>
</tr>
<tr>
<td>Dry Manure production</td>
<td>3 kg/day per head (200 kg cattle weight)</td>
</tr>
<tr>
<td>Gas production/cattle</td>
<td>660 kCal/day</td>
</tr>
<tr>
<td>Consider a village, 500 people</td>
<td></td>
</tr>
<tr>
<td>250 cattle</td>
<td>1.65 x 10^6 kCal/day of gas</td>
</tr>
</tbody>
</table>

1. Village needs:
   - cooking (gas stoves)                                | 0.5 x 10^6 kCal/day                         |
   - Leaves                                              | 1.15 x 10^6 kCal/day                        |
   - Generate electricity @ 25%                          | 340 kWh                                     |
   - (in diesel engines)                                 |                                            |
   - Can power                                           | 10, 5 kW irrigation pumps for 7 hs./day (irrigate 150 hectares) (waste heat = .86 x 10^6 kCal/day) |

2. National Total:
   - 250 million cattle                                   | 1.65 x 10^{12} kCal/day or 600 x 10^{12} kCal/year (Satisfy all rural domestic needs for energy.) |

Organic fertilizer is very useful for the soil. Since it is in the form of a sludge, it is available immediately for use on the soil. Organic fertilizer remains longer in the soil, and there is a gradual release of the crop. There is considerably less leaching and runoff from organic fertilizer than from inorganic fertilizer. In addition,
Organic fertilizers appear to increase the protein percentage of certain crops, such as corn, a very important consideration in a protein-starved country like India.

Thus, the possibility of fertilizer output from a biogas plant, along with the energy output, makes biogasification a very attractive technology.

Biogas plants can be designed to run on agricultural waste, 1 ton of wheat, for example produces 1.75 ton of dry residues. Most of these are eaten by animals. If the yields of wheat were to increase to double or triple their current yields in low-yield areas of India, or if wheat were to be planted as a second crop where no multiple cropping exists, then a substantial increase in crop residues would take place. For example, in our typical village, the wheat crop on 150 hectares could amount to 450 tons. This means 790 t of residue, which, if eaten by the existing 250 cattle, would increase their body weight significantly, thus leading to greater milk output, and also manure output. Assuming that only 50% of wheat residue ends up as manure (or is used directly), this would amount to an increase of $2.4 \times 10^6$ kCal/day in gas, or a 145% increase in gas production. Thus, biogasification can be a self-sustaining-growth technology from the viewpoint of energy output.

However, the present design of the plants suffers from several problems. Among these are:

1. High cost/m$^3$ of gas.
2. Short life, particularly of gas holder.
3. Low gas output/kg of dung, particularly in winter.
4. Nonavailability of standard engines to run on biogas.
5. So far, the standard plants can only be run on cattle or human waste, and not on vegetable wastes.
Almost all of these problems can be traced to the almost complete absence of scientific design concepts from the production units. Very few scientists were involved in designing these plants, and the present design has evolved by trial and error. But recently, many competent scientists have started looking at the problems of biogas plants.

What are the possible solutions?

1. **Low output**: The primary reason for low output/kg, and the high residence time for fermentation, is the low temperature (particularly in the winter months) of the slurry, and the absence of good chemical kinetics. The bacteria simply do not work very well at low temperatures, and the absence of stirring or turbulence reduces the rate of chemical reaction. Surprisingly, we still lack such basic data as the temperature profile in the digester, the pH profile, and the data on output vs. temperature or output vs. turbulence are, by and large, unavailable. There is little doubt that, judging by the data available abroad and a few scattered data from India, the output of a biogas plant, both in terms of m³/kg and m³/day, can be substantially increased by maintaining a temperature of 40-50°C in the digester, increasing the reactivity by turbulent mixing, and controlling the pH of the mixture. Conservatively, a net conversion efficiency of 60% should be feasible, (500 l/kg) and the output/day should be at least twice what it is today for any given volume of digester. Thus, the capital cost/m³ would be reduced by at least a factor of 2 in a proper scientific design.23

Two simple ways of heating biogas plants appear feasible. The first is by using solar energy. Since sun is available over most of India almost every day during winter, providing solar heating should not be a problem. Consider first what energy is needed for maintaining 40°C inside
a digester. This is shown in Table V.

To provide this heat loss of 130 kWh/day, we can use solar energy. Assuming 1 kWh/m² incident energy for 8 hours/day, at 60% efficiency of solar collectors, we need an area of 27 m² of solar collectors. Even if we use metal collectors (we wouldn't), the cost would be ~ Rs. 5000, or a 10% increase over present day costs of the inefficient biogas plants (Rs. 50,000 for 5000 cft/day plants). Thus, solar energy certainly seems feasible.

<table>
<thead>
<tr>
<th>Table V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Requirements of Biogas Plants</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>Need 40°C</td>
</tr>
<tr>
<td>Outside Temperature 5°C</td>
</tr>
<tr>
<td>Ground Temperature 15°C</td>
</tr>
<tr>
<td>Insulate plant by &quot;burying&quot; reducing heat loss.</td>
</tr>
<tr>
<td>At 40°C, residence time = 15–20 days (Use 20).</td>
</tr>
<tr>
<td>Consider a 138,000 l/day (5000 cft/day).</td>
</tr>
<tr>
<td>volume of digestor @ 500 l/kg gas, 1:1 ratio of water:dung</td>
</tr>
<tr>
<td>c = 11,000 l</td>
</tr>
<tr>
<td>assume heat loss of 10°C/day (high!)</td>
</tr>
<tr>
<td>heat loss ~ 11 x 10⁴ kCal/day (1.3 x 10² kWh)</td>
</tr>
</tbody>
</table>

If we run engines using biogas plants of 500 l/kg, then we get 375,000 l/day of biogas, or 2 x 10⁶ kCal/day. Allowing for cooking needs leaves 1.5 x 10⁶ kCal/day, and waste heat from engines at 25% efficiency is 1.1 x 10⁶ kCal/day. So, for a 138,000 l/day plant, waste heat available
is \(4 \times 10^5\) kCal/day, which is 3.8 times the heat needed to keep biogas digester at 40°C with 15° ground ambient. Therefore, waste heat is an entirely feasible means of heating biogas digesters. The economics should be very favorable, since all that is required is a simple water circulation system, a water tank, and a heat exchanger. Even a hand pump for water circulation will do. Of course, a simple fractional kW motor, using electricity generated from biogas, or even a belt driven pump from the diesel generator, could provide the heat circulation. It is not advisable to pass hot gases indirectly (through heat transfer tubings) into the biogas plant, because the temperature will be too high and will kill bacteria. It is much better to heat up water in a tank, and use this water to heat up the biogas plant.

Note that it is important to keep the heat loss from the digester low. The present plants are unsuited for a low heat loss. Consider a typical plant as shown in Figure 13. Note that the gas holder is above ground. Since it is metal, it conducts heat away from the biogas plant, and then the exposed area radiates and convects heat away to the air. It is a very poor design from a thermal viewpoint.

One possible modification would be to "bury" the plant below ground. Since earth temperature, a meter or so below the surface, seldom drops below 15°C, heat losses through the sidewalls are minimized. We can further reduce them by simple insulation, or leaving air gaps in brickwork etc. By eliminating the major heat loss mechanism, (gas holder) we further reduce heat losses. A simple design is shown in Figure 14. Note that we need to provide an external gas storage, which is not a particularly difficult problem. (A simple storage would be a shallow digester tank
lined with polyethylene.) If we need to provide solar heating, one simple arrangement would be as shown in Figure 15. A shallow trough of water surrounds the digester, and the bottom is painted black. A plastic sheet, appropriately anchored, covers the trough, to prevent convective loss. A simple heat transfer loop, operated by a hand pump (or bicycle-powered pump) could complete the arrangement.

2. Elimination of Corrosion: Very simply, corrosion results because of the effect of rainwater on the outside, and chemical attack from the slurry on the inside of the metal gas holder. The simplest solution is to eliminate corrosion by using a long lasting (5 years, at least) paint. Surely, in a country as technologically advanced as India a suitable, long lasting, paint can be found. Alternate ways of reducing corrosion would be to line gas holder with a plastic material, or to eliminate the contact of the metal with the slurry. (My proposed design, Figure 14, achieves this, although this design is by no means optimal.) In any event, solution of corrosion problem is simple, if enough competent scientific effort is put into it.

3. Utilization of Biogas in Engines: Since biogas is 60% methane, there should be no problem in utilizing it to run internal combustion engines. Indeed, many engines have been run on biogas, both within and without India. But again, the data in India are scattered, and the designs have been trial-and-error type. Surprisingly enough, in a country which exports diesel trucks and diesel engines, there is almost no concentrated engineering design work on biogas run diesel or petrol engines. However, the problem is relatively simple and easily amenable to solution.
Fig 13

standard Bio Gas plant
Figure 14
A Low Heat Loss, Buried Biogas Plant
Figure 15
4. The problem of using biogas plants for vegetable wastes of different kinds essentially lies in the proper mixing of waste and water to form a consistent slurry. In addition the different protein and fat contents of different wastes necessitates different treatments (with NaOH, for example) to ensure a uniform residence time inside the digester, and to obtain high conversion efficiencies. There is a large plant running on sugar cane waste at Sugar Research Institute in Kanpur, but work needs to be done on the use of other crops.

In my opinion, efficient, cost-effective biogasification is probably the most important technology for rural applications in India, and the potential is really enormous.
XII. Status of Research and Development in Biogasification.

The Department of Science and Technology is the primary funding agency for research in biogasification in India.

The leading research institute in biogasification is the Indian Agricultural Research Institute (IARI) in Delhi. Khadi Village Industries Commission (KVIC) in Bombay has been the agency responsible for setting up most of the existing biogas plants in villages. They have also done some development work, and have a Gobar Gas Research Station in Bombay.

There are a number of other institutions in India interested in developing gobar gas plants. Among these are Punjab Agricultural University (Ludhiana), Birla Institute of Technology (Pilani), IIT (Sangalora), Sugar Research Institute (Kampur), Amul Dairy (Anand), Aarey Milk Colony (Bombay), Sevagram Ashram (Wardha), Aurville Institute (Pondicherry), Environmental Research Institute (Nagpur), etc. Studies on management of biogas plants have been made at the Indian Institute of Management (Ahmedabad). Even state organizations such as Gujarat State Agro-Industries Corporations are involved in work on biogas plants. Tata Chemicals is also interested in designing efficient biogas plants for use in nearby villages as a public service.

And, then, there is Rambux Singh, perhaps the leading researcher in the field, at Ajitmal in U.P.

In spite of all this activity, the level of sustained scientific and technological effort is low. Almost all the work is subcritical, much below threshold. Sometimes, people who have no competence in the field are getting substantial amounts of money. For example, KVIC is in charge of corrosion research. It would be hard to find a worse mismatch of funding with talent. Surely, National Chemical Laboratory, or IIT's or
Tata Chemicals are in a much better position to achieve a quick solution to the corrosion problem. In general, the effort is poorly organized, subcritical and likely to achieve results slowly. (In fairness to DST, they are aware of this problem, and are trying to evolve a new plan, but they seem constrained by political considerations.)

This disorganized effort must be streamlined if India ever hopes to achieve a significant, efficient and cost-effective use of its biogas potential soon. The talent exists, the motivation exists, the enthusiasm exists, and the economics make sense. The technical problems are relatively simple. The remaining problem is management. A good strategy may be to form four or five fairly large research teams, each consisting of microbiologists to study biological cultures, chemists to study corrosion, and engineers to study structural materials, thermal design, turbulence, solar heating, etc. with a good team leader. Each team would then build perhaps ten pilot plants, each a carefully designed modification from the other plants, and each carefully instrumented to study temperature profiles, pH profiles, etc. Using this approach, a good design, or several good designs, could be evolved in a year's time and then, India could manufacture large scale plants based on these good designs. There are no such research teams in India today.

Among the well qualified for the assembly of such teams are IARI (Delhi), Amul Dairy (Anand), IIT (Kanpur), IIS (Bangalore), Punjab Agriculture University (Ludhiana), CPHERI (Nagpur), etc. The only place where such a team approach is being considered today is Amul Dairy in Anand, where a very dynamic manager has recognized that the potential can only be realized by careful experimentation. Tata Chemicals in Mithapur are
also considering such experimentation. (Their motivation is to improve the very scarce fuel conditions in Saurashtra and help their employees and neighbors). Rambux Singh in Ajitmal has been doing some outstanding experiments on his own.

It is important to note that the effort should be a sustained, full-time effort. One professor spending a few hours every week is not likely to achieve much. If teaching load is too great, then the research money should be enough to free him from teaching for a year. There is no room for subcritical efforts in this field anymore. India has had subcritical efforts for 20 years now, and nothing has come of it.
XII. Utilization of Urban Waste

The cities in India generate considerable urban combustible waste. Ahmedabad, a city of two million, for example, generates 600 t/day. This organic waste can be converted into energy (or fertilizer). The waste in Ahmedabad has an energy content of about $2.7 \times 10^9$ kCal/day, $(3.2 \times 10^6$ kWh/day), or enough for powering a 50 MW power plant for 20 hrs/day at 33% efficiency.

The utilization of waste as an additional fuel in conjunction with coal is a well-known process, and many electric utilities in the U.S. are processing urban waste to separate out the noncombustible parts, and using the combustible parts as boiler fuels. For India, where coal has such a high ash content, the use of urban refuse should pose no major problem.

The urban sewage, going into a sewage treatment plant, also has applications as a gas generator. A sewage plant is a big anaerobic digester.

The plants at Okhla near Delhi, Dadar in Bombay, and Bangalore, are already providing gas to nearby communities. Using 20 kg/year per capita as an average weight of dry human excretion in India, the city of Ahmedabad, to take the same example, should produce $240 \times 10^6$ KCal/day, or enough to satisfy the cooking needs of 240,000 people. Surely, this gas should not be allowed to go to waste. It can be used in an industry set up nearby, if piping the gas to homes is not feasible.

Of course, the sludge from sewage plants is rich in fertilizers, and is already being used on sewage farms in India for producing crops and grasses.
It is also possible to produce composted fertilizer from urban waste (paper, etc.). Ahmedabad has set up a pilot plant to process 1000 tons/day into fertilizer, and other cities in India are following suit.
XIV. Wind Power

Wind power, which is a derivative of solar energy, has become quite popular in the public mind recently. Among its advantages are direct mechanical couplings to irrigation pumps and village industries.

However, unlike solar energy, wind energy has a low potential for India. The reason is simple. Windpower depends upon the velocity of the wind (the energy is proportional to $v^3$). Unfortunately India does not have high wind velocities, unlike countries such as Holland, Denmark, and parts of the U.S. The average wind velocities in India are very low, ranging from annual average of 6 kmph at Allahabad (typical of the Ganga plain) to 17 kmph at Veraval (Saurashtra coast). In contrast, the interior of Holland has monthly average wind velocity of 20-25 kmph, and the coast of Holland has 32 kmph winds. Thus, wind velocities in India, except along the coasts of Saurashtra and Tamilnadu, are too low to be very useful. The distribution of wind velocity in India is shown in Table VI.

Note from Table VI that there is quite a seasonal variation in wind velocity. In particular, winds are very high during monsoon months (June-September), and low during autumn months (November-December). Since India does not generally need irrigation during monsoon months, the applicability of wind power for irrigation must be seriously questioned.

Wind power, however, may be used in conjunction with large, central solar stations. In particular, a series of large windmills along Saurashtra and Tamilnadu coasts, can be integrated into the regional power grids, and provide a complement to solar systems during those months when the solar energy inputs (due to monsoon) are low. Systems studies of large scale windpower need to be done before wind energy can be
considered a viable source. Even, then it will only be a marginal source.

Most of the research on windmills in India is at National Aeronautical Laboratory in Bangalore, and at IIS (Bangalore). Work is being done on sailwing-type windmills, Savonius rotor and NRC (Canada) type rotors. MAL, of course, is very well qualified to handle this work, and has pioneered windpower in India. Perhaps, they may also work on the "mini-tornado" type windpower generator being developed at Grumman Aircraft in the U.S.

The major thrust for wind R&D should be in building large (10kW) machines along the coast and testing out an integrated system.

Table VI: Monthly Average Wind Speeds (in kmph)

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<tr>
<th>No.</th>
<th>Location</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
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(1) Central Observatory (2) H.A.L. (3) Colaba (4) Santa Cruz.

XV. **R&D Policy in India**

The government of India, recognizing the importance of new energy technologies, have appointed the Department of Science and Technology as the main agency for accelerating the development of solar energy and biogasification. DST plans to spend Rs. 60 million over five years to advance solar energy and biogas. While this sum may at first look large, it is well to remember that India is spending about Rs. 400 million per year on nuclear energy R&D (including nuclear medicine etc., but excluding prototype construction costs). Thus, the scale of effort on solar energy is extremely modest. Moreover, keeping in mind that a large (1000 MW) nuclear plant may cost Rs. 10 billion to build, it is clear that the research effort on solar energy (and biogas) is very low in proportion to its potential.

Even more distressing that the low total effort is the poor allocation of the money. The money is, with some exceptions, spend among too many projects, leading to very low level research in any one technology. Generally speaking, money is being distributed in a "sprinkler" fashion, with no real understanding of what is more promising and what is less promising. A good R&D policy demands that more money should be allocated to a project which is more technologically advanced, has greater potential and is nearer commercialization. The ideas which appear promising, but only in the distant future, should receive only minimal funding. Similarly, less promising ideas should receive minimal funding. I would call this a "channelized" approach to R&D. While the "sprinkler" system avoids oversight, it also prevents success. And surely, in a country as sophisticated as India, oversight is unlikely or can be easily corrected.
An equally important strategy is to assemble a critical mass and put a large enough effort in the technologies that do appear more promising and immediate. Two-men teams will never advance any project rapidly. The example of nuclear research in India should be a guide to R&D policy generally. The reason why the nuclear option is open to India today is because Homi Bhabha, with full backing from Nehru, recognized that he had to assemble a large enough body of scientists, and build large enough experimental facilities in one place, to be able to rapidly advance all phases of nuclear work. He started by building up the manpower first, and concentrated on simple reactor systems. Only when the first generation reactors were mastered did he (and his successors) turn to breeders. Whatever they did, they did well, and thoroughly, and in one place, and with one goal: Make nuclear energy work as fast as possible. He achieved the critical mass, and nuclear energy worked.

There is a lesson to be learned from this. Advance of technology demands a sustained effort, a careful choice of options, and then the development of those options. Bhabha could have dissipated his resources into CANDU, PWR, BWR, HTGR, Fusion, LMFBR, Molten Salt Breeder, etc. He didn't. He chose CANDU after some experiments and stuck with it until it worked. Similarly, today LMFBR has been chosen as the breeder option, and DAE plans to build not a trivial unit of a 100 kW, but a prototype of 20 MW, from which useful design experience can be gained which can be transferred to a commercial reactor of 400 MW. Of course it costs money to do all that. But then good industrial development always costs money. The point is that it is better to take a risk and put substantial money into a project and make it work, rather than be cautious, and put money
on all kinds of projects, good, bad or indifferent, with the guarantee that no useful results will be achieved.

In solar energy and biogas, (and coal), the problem is much simpler than the one faced by Bhabha (and Jawaharlal Nehru) in the nuclear field. The scientific talent already exists, and the technologies are simpler (and less expensive). What is needed is a commitment to build pilot plants to test out the more promising ideas, and the courage to redirect R&D efforts into more meaningful and productive areas and organizations.

The absence of industrial R&D has been mentioned before. India simply cannot afford not to enlist its large industrial organizations, both public and private sector, into energy R&D. For example, TELCO and Kirloskar can play a very important role in designing an optimal diesel engine to work on biogas. One would expect them to know more about manufacture and design of diesel engines than KVIC.

Some private charitable foundations in India are taking interest in rural energy development. The Tatas have established Tata Energy Research Institute in Bombay. TERI intends to support outstanding programs and institutions in energy R&D field. It is to be hoped that other leading trusts, such as Birlas, will also support useful, critical programs in biogas, solar energy and energy conservation. Coal conversion is too big a technology and is best left to the government.

I believe that Rural Electrification Corporation is also quite interested in biogasification, and is putting some money into biogas plants. Perhaps, they may be interested in supporting research on biogas plants.
XVI. The Role of External Aid Agencies

There are perhaps three roles that can be played by the external aid agencies in accelerating the development of solar energy, biogasification and better coal utilization in India.

1. Technical Exchange. Since solar energy, in particular, is a fast moving field, with substantial research being done in the West, there is a need to sponsor two-way exchanges of scientists between India and the industrialized nations. The intercourse of ideas, and the intellectual ferment of the larger scientific laboratories in the West are a powerful stimulus for the development of fruitful ideas. Similarly, western scientists spending time in India would better appreciate the problems of India, may contribute to India's development, and also may learn useful ideas from Indian scientists. The learning curve for new technologies (for example, ion implantation) can be shortened considerably by these exchanges.

2. Technical Aid. While India is in a position to make most of the devices itself, some items have to be imported. The case of Silicon has been mentioned earlier. There is a desperate need for sophisticated instruments to measure devices and for some manufacturing equipment. It is not enough to know that a solar cell works or doesn't work. We need to know why or why not. Sophisticated measurements are a very necessary part of research. The philosophy in India seems to be to build everything at home, even if it takes ten years to do so. The philosophy should be: How do I get the fastest advance in a technology that may be crucial to India's development? Surely, an import of initial instrumentation or necessary equipment is justified if the result would be significant advance in solar energy development.
The external aid agencies can help out in this field.

3. **Project Grants.** As explained earlier, pilot plants on a realistic scale, using technologies which appear very promising, and large-scale, concentrated experimentation, are absolutely vital for a significant advance in solar energy, coal gasification (and liquefaction) and biogasification. These pilot plants may be expensive. For example, a 1 MW solar-tower-power may cost Rs. 20-30 million. A coal-gasification plant for 100 t/day of coal to produce gas for a 10 MW power plant may cost Rs. 20-40 million. Perhaps, India does not have money to spare, even though these pilot projects are crucial to demonstrate the feasibility of the technology. The external aid agencies, particularly the World Bank (IBRD) have an important role to play here. Traditionally, the World Bank only gives loans (and IDA soft loans) for established technology. But surely, this is a wrong approach. If rural development is important in the eyes of IBRD, then why not support technologies that appear promising for rural applications, even if they are not proven? Why close off one's options by sticking to past practice? Technology does change, and IBRD should be prepared to support the exploration of alternative technologies. In any event, support for these pilot projects would be an insignificant amount of money compared to the large loans that IBRD traditionally makes. Perhaps, allocating a small fraction of IBRD's lending for energy projects for supporting pilot plant testing of promising technologies would be a good strategy for it to follow. This would certainly make large sums of R&D money available to countries like India, which can use money effectively.
XVI. Economics of Energy

Needless to say, any technology must be cost effective. Of course, we should include both direct, and indirect (environmental, social, etc.) costs and benefits.

The typical economics of energy, using both direct fuel and electricity are shown in Table VII.

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<th>Capital Cost</th>
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<td>CIF/POE</td>
<td></td>
<td>6.7</td>
<td>5.0</td>
</tr>
<tr>
<td>3. Coal-Thermal power (urban)</td>
<td>Rs/kw (p/kwh)</td>
<td>3200</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(rural)</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>4. Diesel Generator (1500 hs/year)</td>
<td>2200</td>
<td>29.3</td>
<td>40</td>
<td>69.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(3000 hs/year)</td>
<td>14.6</td>
<td>40</td>
</tr>
<tr>
<td>5. Nuclear Power (urban)</td>
<td>8800</td>
<td>22</td>
<td>3.0</td>
<td>5.0</td>
</tr>
<tr>
<td>6. Hydroelectric (5000 hs)</td>
<td>4000</td>
<td>12.0</td>
<td>2.0</td>
<td>5.0</td>
</tr>
<tr>
<td>7. Solar (Tower)</td>
<td>No storage (3000 hs)</td>
<td>4400</td>
<td>22</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>With pumped storage (5200 hs)</td>
<td>10000</td>
<td>28</td>
<td>2</td>
</tr>
<tr>
<td>8. Solar + Irrigation (1500 hs)</td>
<td>4400</td>
<td>44</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>(2500 hs (including lighting &amp; battery))</td>
<td>5000</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>9. Biogas Plants (3000 hs/year)</td>
<td>2300</td>
<td>15</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>With Diesel Genr.</td>
<td>4500</td>
<td>29</td>
<td>14</td>
</tr>
</tbody>
</table>
Notes on Table VII

1. Coal cost is Rs. 70/ton, 5000 kC/kg coal.

2. Coal transport cost is for western India.

3. Oil cost is $13/barrel + $1/barrel transport. Cost in item 2 is for delivery to a village.

4. Coal is burnt at 33% efficiency power generation.

5. Capital costs are for new plants. In many cases, represent the best judgement of the author.

6. OTM cost for diesel is 10 p/kwh, fuel cost 30 p/kwh.

7. Transmission costs are ~$250/kw.

8. Annual rate for central generation 15%, diesel generators 20%, to allow for shorter life of diesel.

9. Solar costs are $500/kw for central generation, $500/kw for dispersed generation.

10. Biogasification is for a community size plant, 100,000 l/day, but with advanced design, costing perhaps Rs. 25,000.

Our representative village, producing 400 l/kg, 300,000 l/day would have three plants, each of 100,000 l capacity. There would be three maintenance men, each drawing Rs. 100 per month. We operate biogas plants such that output of one plant is given away free to villagers for cooking -- say 5000 kCal/day per family. The villagers pay for the cylinders. They have to bring in dung, and have the right to take away the fertilizer.

Perhaps the most interesting observations in the table is that biogasification plants are competitive even when cooking gas and fertilizer are given away for free, in return for the villagers bringing in dung for free. The villager pays for the cylinders (low pressure, low cost) and stoves. Alternatively, we can work out the economics including the cost of cylinders, but charge for fertilizer. (See Table VIII).
Note from Table VII that solar irrigation, using solar cells at Rs. 4400/kw ($500/kw) is a technology which will compete very well with present day costs of rural electricity delivery. Similarly, even a large, remote solar tower (central generation) at Rs. 4400/kw will compete with present day nuclear costs. I fully expect high intensity solar-cell costs to be lower than $500/kw in the very near future, especially in India, where tracking systems can be less sophisticated. Note that solar tower costs can be reduced considerably if a suitable geographical location (appropriate hill for mirror placement) can be found. I expect that an intensive search will find such locations in the hilly areas of Rajasthan, Kutch, Saurashtra and northern Gujarat.

Note also that solar cells, even at $800/kw will give power at 70 p/kwh, which is competitive with present day diesel generator pump costs. The fact that many farmers in India have bought diesel generators for standby power, is a good indication of the importance attached by farmers to a reliable irrigation source. Solar energy could very well be an attractive source from reliability viewpoint. (But the only way to find out for sure is to run a few irrigation pumps with solar energy.)

Now let us consider the costs of a biogas system where the state or village owns the cylinders, and sells the fertilizer, but still gives away gas free to those who bring in dung. A 100 litre cylinder could contain enough gas for a day's use of a family under fairly low pressure (10 atmosphere). Such a cylinder could cost Rs. 200 (and a stove, Rs. 100). Thus, the total investment in cylinders for a village would be Rs. 20,000, and the cost of the biogas plus cylinders becomes Rs. 95,000 for a 300,000 l/day plant, or Rs. 32,000 for each 100,000 l/day plant. The new economics per plant are in Table VIII.
### Table VII

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital cost of plant (100,000 l/day) &amp; cylinders</td>
<td>Rs. 32,000</td>
</tr>
<tr>
<td>@ 20%/year</td>
<td>Rs. 6400/year</td>
</tr>
<tr>
<td>Power output (300 days/year)</td>
<td>34,000 kwh/year</td>
</tr>
<tr>
<td>Fertilizer output (N)</td>
<td>1.36 t/year</td>
</tr>
<tr>
<td>@ Rs. 3000/t</td>
<td>Rs. 4000/year</td>
</tr>
<tr>
<td>Net cost</td>
<td>Rs. 2400/year</td>
</tr>
<tr>
<td>Operating Cost</td>
<td>Rs. 1200/year</td>
</tr>
<tr>
<td>Total</td>
<td>Rs. 3600/year</td>
</tr>
<tr>
<td>Fuel cost</td>
<td>10.5 p/kwh</td>
</tr>
<tr>
<td>Cost of diesel generator</td>
<td>Rs. 2200/kw</td>
</tr>
<tr>
<td>@ 20%</td>
<td>Rs. 440/kw</td>
</tr>
<tr>
<td>@ 3000 hs/year</td>
<td>14.6 p/kwh</td>
</tr>
<tr>
<td>Fuel (biogas)</td>
<td>10.5</td>
</tr>
<tr>
<td>OTM</td>
<td>10.0</td>
</tr>
<tr>
<td>Total</td>
<td>35.1 p/kwh</td>
</tr>
</tbody>
</table>

Note from Table VI that the cost of biogas power—even when the cost of cylinders is included—is very low. This is because the residue (fertilizer) is sold to the farmer (Note that we have not even allowed for the K and P content of the fertilizer), and have used a low price for N, fertilizer (Rs. 3000/t).

This is an appropriate place to address the question of size of biogas plants—community vs. individual. The economies of scale, and above all, efficiency, favor community plants, say of 100,000 l/day size. Without efficient plants, there will not be gas left over for other uses, and also, landless or cattleless laborers will not be able to get gas and will continue to burn cow dung directly, at very low efficiency, and
waste the fertilizer value inherent in the dung. Community plants where
gas is given away free up to a limit, can meet the cooking needs of every
family, because of high efficiency, and can still sell power (or fertilizer)
products at an economical rate. Perhaps, this is one of the better ways of solving
the management problem of community plants. But I do not pretend that this
is the only way, or even the best way. No doubt, some field experiments
will provide a better answer.
Conclusions and Recommendations

In conclusion, new energy technologies such as solar energy, biogasification and coal conversion, have the potential and the promise to be really useful in India's development in the very near future. They are not exotic, use mostly proven technology, and are economical. What these technologies need is a high-level, sustained R&D effort to evolve the best designs in the next 2-3 years, so that, by 1980, each of these (particularly, biogas and solar energy) can become commercial on a large scale in India. There is no scientific breakthrough required. What is required is an intensive testing of prototypes on a realistic scale, so that good designs can be selected on the basis of actual field experience.

The major strengths in India in these fields are the high degree of enthusiasm, the large mass of very talented scientists and engineers, and the recognition by the national and state governments of the importance of these technologies. The major weaknesses are the waste of scarce resources over too many marginally productive research efforts, the absence of good research teams with critical mass and support, the unwillingness to take educated risks, the reluctance to do real-life intensive, pilot plant testing, and low level of resources for R&D. It is appropriate to remember that the proof of the pudding is in eating, not in writing cookbooks and inventing new recipes.

The external aid agencies have an important role to play in bridging the resource gap, and in providing seed money for prototype testing.

Finally, energy conservation has the potential, and probability, of a significant reduction in energy consumption/unit output in India. The
Technology is, by-and-large, proven, already exists, and is also economical in many cases. What is needed is an intensive study, by each industry, and by national organizations, on what technology is best, and how can it be implemented.

Recommendations:

In my opinion, implementation of solar energy, biogas and coal conversion should be achieved on a priority system which depends on the potential and probability of success. The following breakdown is meant as a rough guide to the technology.

<table>
<thead>
<tr>
<th>Energy Strategies</th>
<th>High Priority</th>
<th>Medium Priority</th>
<th>Low Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Solar Energy:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A. Photosynthesis:</td>
<td>Village woodlots</td>
<td>new high-yield trees</td>
<td>Algal culture</td>
</tr>
<tr>
<td>B. Thermal:</td>
<td>Industrial hot water, simple concentrators, solar stills, cookers</td>
<td>crop drying, refrigeration, skytherm-space-heating, high temperature pumps</td>
<td>Air conditioning, HW space heating, hot water heaters, solar pumps (low T)</td>
</tr>
<tr>
<td>C. Electric Generation:</td>
<td>High intensity solar cells</td>
<td>High intensity Thermal generation (towers)</td>
<td>Low temperature turbines, Helio-hydro-electric</td>
</tr>
<tr>
<td>2. Biogasification:</td>
<td>High efficiency plants (500 l/kg), solar-heated plants, engine development, non-corrosive plants, low cost stoves, low cost cylinders</td>
<td>2-stage and linear Human waste plants, vegetable plants waste plants</td>
<td></td>
</tr>
</tbody>
</table>
3. Urban waste: **High Priority**
   Utilization of sewage gas, composting/burning of solid waste

4. Coal Conversion: **Medium Priority**
   Low-BTU gasifier, combined power plant & chemical plant
   **Low Priority**
   Coal liquefaction
   High-BTU gas

5. Wind Energy: **High Priority**
   Pilot plant for large windmills
   "Vortex" windmill

6. Energy Conservation: **Medium Priority**
   Conservation in industrial processes, dieselization of cars, high efficiency electric power, systems study of buses, special bus lanes, high efficiency appliances, better building designs, total energy systems
   **Low Priority**
   Electrification & dieselization of trains

7. Zero-priority Systems: **Low Priority**
   Ocean-thermal-difference, solar satellite power, MHD.
References

4. Economic and Political Weekly (Bombay, India) 9, 2138 (1974).
12. Power Engineering,


19. Ref. 14, Section on Algeas.


22. Assuming a use of \(0.3 \times 10^6\) kCal/capita-year, the typical use for kerosene stoves in India. We are assuming that efficiency of biogas stoves will be higher than direct cow-dung burning, an assumption well supported by facts. See Ref. 20.

23. Ref. 9.

24. A. Poole, Ref. 21, p. 269.

25. 20 kg/year is a low estimate: An adult eats about 0.5 kg/day, and may excrete 0.2 kg/day.


Appendix A

In this technical appendix, I briefly indicate my ideas on solar cells, and what may or may not work in India. This appendix is meant for the specialist in solar cells, and the general reader may find it too technical for his interests.

1. High Intensity Solar Cells

There is no doubt that High Intensity Solar Cells work. Si has worked at 1000-1200x, and GaAs at 1700x sun intensity. The technology is simple. Briefly, the secret of high intensity solar cells lies in a slight redesign of solar cells to achieve high efficiency even at 1000x concentration. The following are important considerations in the design.

A. High quantum yield. A good anti-reflection coating, and a good collection efficiency for photo-generated carriers, are necessary for a high quantum yield. For Si, this means shallow junctions (≈ 0.2 – 0.3 μm for diffused layers, 0.4 μm for ion implanted-diffused layers). Ion implantation, in particular, offers a real possibility for achieving high surface doping and good minority carrier diffusion lengths in the junction layers. But, diffused layers will also work.

To keep surface recombination down, it will be necessary to grow a thermal oxide. For AR, it may be necessary to use a second insulator layer, with refractive index 2.

Perhaps, it will also be necessary to use surface etching, either chemical or by sputtering, etc., to roughen the surface, reducing reflection.
For GaAs, high quantum yield almost certainly means a heteroface of Al GaAs. LPE or VPE (epitaxy) will be necessary.

B. High Voc. Voltage should be kept high, and the best way would be to use $10^{16} - 10^{17}/\text{cm}^3$ doped p type, 10 μsec material. A voltage of > 0.6 should be the goal in Si.

C. Low contact resistance. Both the front and back contacts should have minimal contact resistance at high current densities. $10^{20}/\text{cm}^3$ doping is necessary in Si.

D. Low sheet resistance between metal fingers. Keep fingers close. 100 μm should be close enough.

In my opinion, Si is the material to use. Goal should be 15% efficiency under AM1 sunlight. (The best efficiency has been 20%.) GaAs technology is too sophisticated, and I am not convinced that it is that much better anyway. Temperaturewise, it is, but that may not be a crucial advantage.

The best institutes in India for Si work are CEERI (Pilani), TIFR (Bombay), ECI (Hyderabad) and SSPL (Delhi), (TIFR perhaps should be entrusted with the epitaxial growth of Si to product 10 μsec, $10^{17}/\text{cm}^3$ material, and also to work on epitaxial Si solar cells.)

The ideal places for GaAs work are TIFR and SSPL (Delhi). SSPL has a lot of experience with GaAs, and it would be better to entrust them with GaAs solar cells, rather than for CEL to set up a new facility.

2. Ribbons

I do not see any advantage in a large scale effort on Si ribbons at this stage in India. It is too new for India. Perhaps, NPL (Delhi) should have a small research effort, but that is all.
3. Polycrystalline Sc.

The materials of choice should be Si, CdS and GaAs. Poly Si, particularly by CVD on graphite, looks extremely promising. Poly GaAs, and poly CdS should also be tried. One major effort should be in Cu$_2$S-based cells.

It is well to bear in mind that a "dépletion-mode," Schottkey barrier solar cell looks very promising for poly materials. We only need grain sizes of a few μm in GaAs, at concentration of about 10$^{14}$/cm$^3$. For Si, we need over 10 μm grains, 10$^{13}$/cm$^3$ material. That is hard, but not unfeasible.

The major places are NPL (Delhi) and IIT (Delhi). But the efforts in each place are too small, and should be expanded if quick results are to be achieved.

The major thrust of all solar cell activity in India at present should be on a high intensity Si Solar Cell, at 50-100x concentration. A 1kW, 15% efficiency unit should be the goal, to be set up in 1977 for actual field tests. Slow-tracking concentrators seem more appropriate for India. If necessary, the initial solar cells should be imported, just to gain field experience. Above all, the effort should be an all-out, no holds-barred enterprise, with one goal: Make it work in 1977.
Appendix B.

Acknowledgments

In addition to the people mentioned in the preface, I am particularly grateful to the following people and institutions for their help and kindness.

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This list is not all exhaustive, and I offer my sincere thanks to many others who have helped me do my research.
Appendix C

Section on Units:

The unit of currency is the Indian Rupee (Rs.). 1 U.S. $ = 8.80 Rs. The energy units are either in kiloCalories (kC) or kilo-watt-hours (kWh). 1 kWh = 850 kCal. 1 kC = 4 BTU, 1 kC = 4.18 kJoules. The unit of mass is kilogram (kg). 1 kg = 2.2 lbs. The ton used in the text is the metric tonne (1000 kg). The power plants are generally expressed in MW (Megawatts). 1 MW = 1000 kW. The unit of volume is a litre.

1 litre = 1000 cc
1 cft = 27 litres
1 m³ = 1000 l

The unit of area is a square meter. Hectare is 1/100 of a square kilometer, or 10,000 m². 1 hectare = 2.5 acres.
Appendix D.

Abbreviations of Institute Names

AZEL - Arid Zone Research Lab., Jodhpur
BARC - Bhabha Atomic Research Center, Bombay
BHREL - Bharat Heavy Electricals Ltd., Delhi
BITS - Birla Institute of Technology and Science, Pilani
CBRD - Central Building Research Design Institute, Roorkee
CEERI - Central Electronic Engineering Research Institute, Pilani
CEL - Central Electronics Ltd., Delhi
CEA - Central Energy Authority, Delhi
CRFI - Central Fuel Research Institute, Dhanbad
CPHERI - Central Public Health and Environmental Research Institute, Nagpur
CSMCRI - Central Salt and Marine Chemicals Research Institute, Bhavnagar
CSIR - Council of Scientific and Industrial Research, Delhi
DAE - Department of Atomic Energy, Bombay
DST - Department of Science and Technology, Delhi
FPC - Fuel Policy Committee
FRI - Forest Research Institute, Dehradun
GTRE - Gas Turbine Research Institute, Bangalore
GSFC - Gujarat State Financial Corp., Ahmedabad
IARI - Indian Agricultural Research Institute, Delhi
ICAR - Indian Council on Agricultural Research, Delhi
IIS - Indian Institute of Science, Bangalore
IIT - Indian Institutes of Technology (location)
ISI - Indian Statistical Institute, Delhi
KVIC - Khadi Village Industries Commission, Bombay
NAL - National Aeronautical Laboratory, Bangalore

NCL - National Chemical Laboratory, Pune

NPL - National Physical Laboratory, Delhi

NPC - National Productivity Council, Delhi

ORC - Operations Research Group, Baroda

PRL - Physical Research Laboratory, Ahmedabad

SSPL - Solid State Physics Lab., Delhi

TIFR - Tata Institute of Fundamental Research, Bombay