Feasibility Study of the Utilization of Solar Energy for Large Scale Power Production in the State of Florida

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FEASIBILITY STUDY OF THE UTILIZATION OF SOLAR ENERGY FOR LARGE SCALE POWER PRODUCTION IN THE STATE OF FLORIDA

BY

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RESEARCH REPORT

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Orlando, Florida
1975
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ABSTRACT

The objective of this paper is to investigate the feasibility of large scale electric power generation in the state of Florida by means of solar conversion. Such systems convert solar radiation directly to electricity or to thermal energy and subsequently to electricity. With the latter method, solar energy is initially collected and converted to heat at high temperature through a working fluid. The heat is then used to power conventional heat engine generator systems.

Several methods have been proposed for converting sunlight to useful work. The most promising of these will be examined from a technological and economic viewpoint.
CHAPTER I

INSOLATION AND POWER UTILIZATION

To estimate the amount of solar radiation available in the state of Florida for a given month, three regions were examined: Miami, Orlando and Tallahassee. For each region the monthly averages of total solar radiation on a horizontal surface were computed based on extraterrestrial radiation and the average amount of daily sunshine. Figure 1 shows the resulting seasonal distribution of solar radiation. Based on these calculations, the average daily radiation on a horizontal surface for the state of Florida is 17,860 KJ/m$^2$ or 1573 BTU/ft$^2$.

Figure 2 depicts the history and forecast of energy production by the Florida Power and Light Company.


Fig. 1. Monthly distribution of solar radiation on a horizontal surface.
To estimate the amount of electric energy production by all electric utilities, it was assumed that the ratio of 1971 Florida Power and Light sales to 1971 total Florida electric energy production would remain constant. The resulting data is presented in Figure 2.

**Fig. 2.** History and forecast of energy consumption in the state of Florida.
Large amounts of energy must be collected for electric power generation. With 1573 BTU/ft$^2$ being the average daily solar radiation, one square mile of Florida receives $16 \times 10^{12}$ BTU of energy per year. From Figure 2, the estimated electric energy production for Florida in the year 1980 is 163.5 million MWH, which is equivalent to $5.578 \times 10^{14}$ BTU. The area needed to collect this much energy is therefore equal to 34.9 square miles. That is 34.9 square miles of land receives on the average in one year the equivalent of all anticipated 1980 Florida electric energy production. At 10 per cent conversion efficiency, 349 square miles or 0.64 per cent of the total land area, could produce the amount of power that will be needed in the year 1980.

It is therefore apparent, that Florida is a possible candidate for the implementation of solar conversion technology on a large scale.
CHAPTER II

PHOTOVOLTAIC ELECTRIC POWER GENERATION

A promising method of utilizing the sun's energy in the distant future is by directly generating electricity from sunlight through photovoltaic cells. Silicon crystal "p-n" junction cell arrays have provided highly reliable power for almost all unmanned spacecraft launched during the past decade.

In their present stage of development, individually produced silicon cells can be expected to operate with conversion efficiencies of approximately 15 per cent. Mass produced cells however, exhibit efficiencies closer to 10 per cent.¹ Significant efforts are being made to reduce the cost and improve mass production techniques of continuous ribbons of silicon from which solar cells can be made.²

¹Stanford Research Institute, Energy Supply and Demand Situation in North America to 1990, Volume 9: Energy Technology (Stanford, California, 1974), p. 228.

To understand the efficiency limitations of a photovoltaic cell one must examine its spectral response with respect to the available energy from the sun. A silicon cell will convert sunlight up to a wavelength of 1.15 \( \mu \text{m} \). This corresponds to a minimum of 1.08 electron volts needed to excite an electron to a higher energy level. At shorter wavelengths, below 0.45 \( \mu \text{m} \), silicon cells are inefficient since excess energy is wasted during the reaction. The spectral response of a silicon cell for a constant light intensity is shown in Figure 3.\(^3\)

Fig. 3. Normalized spectral response of a silicon solar cell. Relative output current, I versus wavelength.

Figure 4 shows the relative spectral output of the sun outside the earth's atmosphere. As a consequence of the shift in the two curves (Figure 3 and 4), only about 45 per cent of the available sunlight can be used to release electrons. Furthermore, only half of this energy is recoverable in the form of an electric current.\(^5\)

Thus the theoretical efficiency of photovoltaic devices is limited to approximately 20 per cent.

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The abundance of silicon makes it an attractive choice as a photovoltaic converter. However, in the quest for low cost, mass-produced cells, materials other than silicon have been shown to be suitable candidates.

Cadmium sulfide photovoltaic cells with a vapor deposited film can be produced at greatly reduced costs. However, the major task of increasing both their life and efficiency still remains. ⁶

Another approach for cost reduction is the use of concentrators. Since a major portion of the power plant capital investment is directly proportional to the surface area of collectors needed, costs can be significantly reduced by initially focusing the available sunlight. This is further discussed in Chapter III, page 20 in view of recent work performed by Drs. Meinel and Meinel at the University of Arizona.

The Federal Energy Administration foresees major cost reductions in silicon arrays based on a ten year research and development program. According to the guidelines of this program, $500/KW arrays would be commercially available by 1985. Not until the early 1990's would a more reasonable $100/KW array become feasible. This is indeed an ambitious goal, since present day arrays

⁶Ibid., pp. 207-15.

Recent awareness of the limited nature of fossil fuels has led to the "total energy concept" in the analysis of new energy systems. According to this concept all input energy associated with a system, from raw material acquisition through final product implementation, is compared to potential output. The net balance can then be used to evaluate the total impact of a new system on total energy consumption. Current manufacturing techniques associated with individually grown silicon solar cells are far too costly and time consuming. To result in a favorable energy balance, extremely large increases in production rates are necessary. Also, new processes must be developed which would integrate multiple operations in the fabrication of solar arrays.

It is therefore apparent that photovoltaic electric systems are not likely to have a significant impact on large scale power production in the near future. Unlike the other forms of solar energy conversion discussed in this paper, photovoltaic systems will not become feasible until a major technological breakthrough is achieved. Today's solar cell manufacturing techniques are not geared
for delivering arrays at mass production rates. Thus far, attempts to correct this situation have been at the expense of conversion efficiency.

Improvements in solar cell technology leading to higher efficiency and substantially lower fabrication costs will undoubtedly be seen within a decade. However, in view of today's world energy crisis, other methods of conversion which are based on well developed technologies, should be given top priority.
CHAPTER III

ELECTRIC POWER GENERATION BY MEANS OF THERMAL CONVERSION

Two types of solar thermal conversion systems have been proposed. The first, designated as a "solar farm", consists of numerous solar collectors which concentrate solar radiation on focal tubes which contain a working fluid. This fluid transports the thermal energy from each individual collector to the thermal-to-electric converter.\(^1\)

The alternate method, known as the central receiver system, consists of a large number of nearly flat tracking mirrors (heliostats) which reflect solar energy to a central collector at the top of a tower. This concentrated energy is transferred to a working fluid which in turn is used to drive a thermal-to-electric converter.\(^2\)

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The heat transfer mode and working fluid are dependent on the temperature and design of a specific thermal conversion system. The extremely high levels of power density at the boiler of a tower top collector will probably necessitate the use of liquid metals for heat transfer. A good candidate for this purpose is liquid sodium, since the necessary technology has already been developed for nuclear reactors.  

In the case of the solar farm, heat collected by a fluid flowing through the pipes could be stored in a phase-change salt or a molten eutectic and used to produce steam when needed to drive a turbine. In addition to the forced circulation of metals such as liquid sodium, fused salts may be utilized to transport thermal energy to electrical energy converters. Forced circulation of gases such as helium, in a closed cycle, is also a feasible alternative.

Thermal-to-electric conversion for large scale operation can best be achieved with a steam turbine Rankine cycle or a gas turbine Brayton cycle. In case of lower collector temperatures, a suitable organic vapor turbine

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3 Ibid., p. 6.

Rankine cycle can be used instead of a steam power system. Organic vapor turbines have been used increasingly for power cost reduction in chemical processing industries. Although an open-cycle gas turbine is not a good choice due to its low thermal efficiency, a closed Brayton cycle utilizing helium is a potentially good candidate.

Common to both systems is the requirement of large areas of collector surface. A summary of the various types of collectors available is presented in Table 1. Although the flat plate collector is economically superior, requiring no tracking mechanisms and being least costly to manufacture, it does not result in sufficiently high enough thermal-to-electric conversion efficiency due to its presently low collection temperature. It is for this reason that more emphasis is being put into solar energy concentration techniques which result in higher collection temperatures and in turn higher overall conversion efficiency. Figure 5 illustrates this temperature dependence.

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5 Ibid., sec. III, p. 12.

6 Ibid., sec. III, p. 8.

<table>
<thead>
<tr>
<th>TYPE</th>
<th>TEMPERATURE OF APPLICATION</th>
<th>COLLECTION METHOD</th>
<th>TRACKING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat plate</td>
<td>approx. 300°F</td>
<td>Beam &amp; diffuse radiation absorbed directly on surface.</td>
<td>None</td>
</tr>
<tr>
<td>&quot;Planar&quot; with highly selective surface, a/e≈50</td>
<td>approx. 700°F</td>
<td>Double-cusp reflector directs radiation to absorbing pipe. Beam &amp; diffuse radiation collected.</td>
<td>None</td>
</tr>
<tr>
<td>Line Focus</td>
<td>up to 1000°F</td>
<td>Energy concentrated on focal tube (containing working fluid) by means of parabolic mirrors. Only beam radiation collected.</td>
<td>1-D min.</td>
</tr>
<tr>
<td>Point Focus</td>
<td>up to 2000°F</td>
<td>Large number of mirrors reflect solar energy to a central collector at top of tower. Only beam radiation is collected.</td>
<td>2-D</td>
</tr>
</tbody>
</table>
Fig. 5. Net system efficiency versus collector temperature for solar thermal power system.

The conversion of solar energy to thermal energy requires the use of various design techniques. The most promising to date is the use of selective surfaces. By examining the spectral characteristics of solar radiation, (Figure 6), it is evident that approximately 98 per cent of incoming solar energy outside the earth's atmosphere is at wavelengths less than 3.0 microns.
Fig. 6. Normalized spectral distribution of blackbody radiation. Emissive power, E versus wavelength.
However, as can be seen from Figure 6, a very small amount of energy is emitted from a blackbody whose temperature is 500°K, at wavelengths less than 3.0 microns. The amount of energy is in fact less than 1.5 per cent.  

With this in mind, it becomes desirable to select surfaces which exhibit high absorbtivity for solar radiation (.3 to 2 microns) and low emissivity for thermal (infra-red, > greater than 3 microns) radiation. Although no natural materials exhibit these characteristics such "selective surfaces" can be made artificially with the use of thin, film coatings. Typical spectral characteristics obtained with this method are shown in Figure 7. Additional collector effectiveness can be achieved by selective coating of the inside surface of the collector cover-glass. By achieving high reflectance in the infra-red, emitted radiation is redirected on to the absorber surface. In this manner, a greater percentage of incident radiation is converted to thermal energy.

The solar farm concept proposed by Drs. Meinel and Meinel of the University of Arizona incorporates the aforementioned "selective surface" technology to achieve the necessary temperatures for extracting heat efficiently.

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8Duffie and Beckman, Solar Energy Thermal Processes, pp. 68-71.
Fig. 7. Absorbtivity or emissivity versus wavelength for typical "selective surface".
On the basis of today's selective surface qualities, whose emissivity is on the order of .35, it becomes necessary to concentrate sunlight by a factor of two to four with the use of parabolic mirrors in order to reach the desired temperature of approximately 1000°F.

In a more recent report the Meinels have discounted the use of concentrators as a practical solution to solar energy collection due to the mirror's sensitivity to weather and the high cost of tracking equipment. The solution proposed is the use of "planar" collectors with highly selective surfaces (a/e ratios on the order of fifty). This would produce collector surface temperatures on the order of 600°F and a net system efficiency of approximately 25 per cent. ⁹ An estimate based on using selective absorbers without concentrating lenses brings the cost of this system to $300/KW. ¹⁰ It must be emphasized that this cost is highly dependent on the degree of development of the selective surface technology in the near future.


The alternate method of large scale solar energy utilization involves the use of a central receiver onto which reflected solar radiation is focused. The central receiver concept has several advantages over flat plate collectors. Most important is the fact that heat is collected at approximately 1000°K, resulting in high efficiency. Also the heat transport method from receiver to turbomachinery is simplified since heat is collected in one area.

The major drawbacks of the system are the loss of the diffuse component of radiation since it cannot be focused. Also the necessity of equipping mirrors with solar-tracking devices, and tower construction make this system approximately two to three times more expensive than the "solar farm" concept. Table 2 shows a cost breakdown for a typical 100 MW central receiver power plant, based on average insolation and land costs in the state of Florida.

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### TABLE 2a

100MW CENTRAL RECEIVER POWER PLANT

<table>
<thead>
<tr>
<th>Item</th>
<th>$</th>
<th>$/KW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land 600 acres @ $1500/acre</td>
<td>900,000</td>
<td>9</td>
</tr>
<tr>
<td>Mirrors (heliostats) 1.0 Km @ $30/m</td>
<td>30,000,000</td>
<td>300</td>
</tr>
<tr>
<td>Central receiver tower</td>
<td>4,000,000</td>
<td>40</td>
</tr>
<tr>
<td>Thermal-to-electric power conversion equipment</td>
<td>13,500,000</td>
<td>135</td>
</tr>
<tr>
<td>Thermal storage</td>
<td>9,000,000</td>
<td>90</td>
</tr>
<tr>
<td>Interest and miscellaneous</td>
<td>16,400,000</td>
<td>164</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>73,800,000</strong></td>
<td><strong>738</strong></td>
</tr>
</tbody>
</table>

---

CHAPTER IV

CONVERSION OF ORGANIC MATERIALS TO FUEL OR ENERGY

According to a study¹ sponsored by the National Science Foundation, one of the most developed techniques for solar power utilization is for the purpose of converting organic materials to fuel. This method is currently in the pilot plant demonstration stage of development. This chapter will consider the feasibility of direct combustion of organic wastes or their conversion to fuels by the methods of bioconversion or pyrolysis.

To evaluate the impact organic waste conversion would have on Florida's electric power generation, one must consider the availability of organic wastes. On the basis of 2.5 million head of cattle, the expected dry organic waste would amount to approximately 2.8 million tons per year.² If 20 per cent of this matter is assumed to be recoverable, then about 0.5 million tons of organic matter would be available for energy recovery each year.


²Ibid., p. 25
Urban waste generation is approximately five pounds per person per day. With a present population of 8.4 million, the state of Florida can be expected to produce 7 million tons of waste material per year. Again, assuming a 20 per cent recovery rate, this reduces to 1.4 million tons of useful matter for energy conversion. The total animal and urban solid waste available is therefore on the order of 2 million tons per year. Assuming an average heat content of 15 million BTU per ton, this matter has the potential of delivering $30 \times 10^{12}$ BTU of energy per year. This is equivalent to 8.8 billion KWH, or about 9 per cent of the total electric energy production by Florida's electric utilities in 1975. A 20 per cent recovery rate is not an unreasonably small figure considering the dispersion of the population and farmland, in Florida.

Power production from solid waste combustion is already practiced commercially on a limited scale. Technical feasibility is therefore established. The uncertainties which remain are primarily related to establishing economic feasibility for large scale implementation. Specifically, the cost of collection and transportation may be excessive using existing techniques.

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Organic materials can also be converted to fuels by several chemical or biological processes. Biocconversion to methane has been applied for many years for domestic sewage processing. Pyrolysis, a process of destructive distillation, has also been used widely in the production of methanol and other organic by-products. Significant improvements in efficiency have been made for this process and about two barrels of oil per ton of dry organic material is obtainable. The balance of fuel would be used to operate the facility. Based on the availability of 2 million tons of waste material per year, this process could deliver 4 million barrels of oil yearly. This corresponds to a heating value of 6.8 billion KWH, or approximately 7 per cent of Florida's total electric energy production in 1975.

Conversion of organic materials to fuels appears to be a good near term source of energy. Since all of the ground work has already been laid, a competitive system can be made operational within five years.

CHAPTER V

COMBINED SYSTEMS

The methods of solar conversion discussed thus far were entirely dependent on Florida's high level of available insolation. There is, however, another form of extractable energy unique to the state of Florida. It is the thermal energy of the neighboring Gulf Stream. Solar collectors could be used in conjunction with an ocean thermal cycle, which would economically optimize both systems.

The Gulf Stream transports water at the rate of 25 to 30 million m\(^3\)/second within the Florida Straits. The thermal difference between the surface at 24°C, and a 10°C heat sink at a depth of 1200 feet\(^1\) would permit a theoretical Carnot efficiency of approximately 5 per cent. A temperature profile corresponding to the latitude of Jacksonville, Florida is shown in Figure 8. The technology required for ocean thermal energy conversion is presently

Fig. 8. Temperature profile (°C) across the Florida current along latitude 20°30'N. Depth in meters.

available and fully developed. The shipbuilding and oil drilling industries have the necessary experience and know-how to implement a viable system.²

There are several reasons for combining an ocean thermal conversion system with a solar thermal generating plant as described in Chapter III. The most significant effect is the reduction in collecting surface area required. By substituting part of the generating plant with a suitable ocean thermal cycle the capital investment can be

sizeably reduced.

A combined system can be sized to operate continuously, 24 hours per day. Since power consumption is at a peak during hours of sunshine, and minimal at nighttime the output would be in phase with demand. Transmission of electricity via cable would sizeably reduce the need for storage. Since daytime conversion would be at a much higher efficiency, some excess energy could then be stored in the form of electrolytically generated hydrogen for use during periods of extreme overcast. Even then, these requirements could be minimal due to the uninterrupted energy from the ocean thermal cycle.

Another benefit of the combined floating power plant would be in the form of land reclamation. With increasing population densities, the large land areas needed for power generation are becoming costly and scarce. Off-shore locations appear to be reasonable alternatives. Large scale implementation of such systems could however result in irreversible ecological changes. These effects would have to be thoroughly investigated prior to making any major economic commitments.

Development experience in ocean thermal energy conversion is based on a Rankine cycle demonstrated in 1929, utilizing sea water as the working fluid. This plant required operation at very low pressures using large low
efficiency turbines. In addition, the problem of sea water corrosion made this method unattractive. Two alternatives have been proposed for improving this cycle for present-day application.³ The first involves the use of controlled evaporation. With this method, sea water is evaporated in vertical chutes with decreasing pressure. This stream is then directed through an expansion turbine and subsequently into a condenser where it is cooled by ocean water without mixing. Consequently, fresh water is produced in addition to electric power, and sea water erosion is reduced to a minimum. This cycle does, however, retain the need for a large low efficiency turbine.

The second approach involves the use of a closed Rankine cycle with propane or ammonia as the most likely working fluid candidates. This requires the addition of a boiler but the higher working pressures result in the use of smaller, more efficient turbines. By adjusting the operating depth of the boiler and condenser, pressure differences can be balanced resulting in thinner and less expensive hardware.

Using propane as a working fluid, sea water would be vaporized at about 150 PSI and recondensed at about 110 PSI. These pressures are sufficiently low to

enable an equilibrium to be established at a depth of a few hundred feet. The pressure drop across the turbine, on the other hand, is high enough for the use of more efficient turbines.

Ammonia, as a working fluid, is especially attractive due to its high heat transfer coefficient. The superior heat transfer characteristics of ammonia compared to propane, would result in a smaller boiler and condenser. Pressure characteristics are about the same as in the case of a propane cycle.

Preliminary cost estimates of ocean thermal systems without solar collectors have shown the concepts to be in the $200 to $400 per Kilowatt range. It is therefore likely that a combined system, utilizing a higher overall conversion efficiency and non-tracking collectors would fall into the higher end of this price range.

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CHAPTER VI

ECONOMIC CONSIDERATIONS

With the exception of photovoltaic conversion, the technology associated with the various methods presented in this paper appears to be well developed. From an economic viewpoint, a good deal of progress is yet to be made. Large scale utilization of solar energy involves tremendous capital investments. This is especially true in the case of solar cell array costs. Today's manufacturing techniques are not geared for outputting arrays at mass productions rates. Instead, silicon crystals are individually grown as was done for the highly budgeted space program. Extensive work is being done to correct this situation, but a dramatic decrease in costs should not be expected in the near future. Solar thermal collector technology is much closer to achieving an economically feasible system. As was shown in Chapter III, a solar farm utilizing non-tracking collectors could probably be built with an investment of $300 per Kilowatt, which is slightly more than the capital investment for a nuclear power plant. This concept assumed successful progress and implementation of selective surface technology.
To achieve reasonably high temperatures without selective surfaces, solar concentration techniques must be employed. However, as was seen in the case of the central receiver power plant, the resulting system cost is more than doubled.

In the case of a combined ocean thermal-solar power plant, the economic picture looks more promising. Since the plant would be designed to operate in conjunction with or independently of solar collector input, power generation could begin before total plant completion. This would mean a faster return on the investment. Also, significant developments in collector surfaces could be incorporated into the plant without major power output disruption. The potential for producing and selling excess hydrogen is another economic advantage of this concept. Although the cost estimate for such a system is on the order of $400 per Kilowatt, this is not prohibitive if construction is coupled with favorable tax laws and interest rates. A summary of the capital costs for the various conversion systems discussed in this paper is presented in Table 3.

Fuel production from biological or chemical conversion of organic matter is another area which looks economically feasible for Florida. Preliminary fuel cost estimates using the various methods discussed in this paper are between one and two dollars per million BTU.
This is quite competitive with today's thirteen dollars per barrel of imported crude oil. Although utilization of organic wastes to produce fuel would contribute less than 10 per cent of Florida's energy requirements, the potential environmental benefits are significant. With an ever increasing population density, urban waste disposal problems have become more noticeable in recent years. By early implementation of fuel generating plants, Florida could development the technology slowly and avoid the hardships of today's larger cities.

TABLE 3

CAPITAL COSTS BASED ON NEAR TERM TECHNOLOGY

<table>
<thead>
<tr>
<th>CONVERSION SYSTEM</th>
<th>$/KW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Thermal Non-Tracking Collector Farm</td>
<td>300</td>
</tr>
<tr>
<td>Combined Ocean Thermal-Solar Collector</td>
<td>400</td>
</tr>
<tr>
<td>Central Receiver</td>
<td>750</td>
</tr>
<tr>
<td>Photovoltaic</td>
<td>30,000</td>
</tr>
</tbody>
</table>
CONCLUSION

Land based solar thermal conversion systems are not likely to have significant impact on Florida's large scale electric power production in the near future due to economic considerations. The optimistic cost estimates presented in this paper assume significant development of the selective surface technology and a major reduction in capital costs of solar collectors. In spite of this, the "solar farm" concept exceeds current nuclear power plant costs by 25 per cent. The central receiver system is at best two to three times as costly as the conventional nuclear power plant.

Systems utilizing photovoltaic cells will not be practical for large scale application until a major technological achievement occurs in the manufacturing process of solar cell arrays. Today's individually grown silicon cells are by far too costly for the large collector areas that are required.

Of the various methods investigated, a combined system utilizing ocean thermal gradients and non-tracking collectors seems most promising for large scale application in the state of Florida. The ideal location of the Gulf Stream and a high level of insolation make this
system highly plausible. From a technological viewpoint, no major breakthrough in the off-shore construction industry is required. Collector prices can be expected to decrease in the near future as more research money is being put into this area. The federal government is also considering various economic incentives in order to stimulate domestic energy production from non-depletable sources. A system using ocean thermal gradients and sunshine would certainly qualify when such legislation is put into effect.

Another area which appears to be well into the demonstration stage of development is the production of fuel from organic waste material. Although this method would supply less than 10 per cent of Florida's energy needs, the environmental benefits to be derived make it a worthwhile endeavor. Since crude oil prices have drastically risen, and the limited supply is likely to keep these prices up, the cost of reducing organic wastes to fuels has become a competitive process.
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