The Sun – Major Energy Resource for the Future

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With rising standards of living, the per capita energy consumption is increasing rapidly all over the world. The limited reserves of fossil fuels may be exhausted by the middle of the next century. This crisis situation has forced technologists to turn to alternate sources of energy, like wind energy, ocean thermal energy and solar energy. All the above forms of energy are indirectly derived from solar energy.

In this article a short account of the amount of solar radiation reaching the earth, its spectral distribution and its interaction with the earth's atmosphere is presented. A brief discussion is given on hydro-power, wind-power and ocean thermal energy conversion as indirect techniques of utilization of solar energy. Solar energy can also be directly converted into heat and electricity. Techniques for such direct conversion, with special reference to photovoltaic generation of electricity, are also described in this article.

Introduction

With growing population and industrialization, the global demand for energy has been increasing. *Figure 1* shows the trends in population growth and per capita energy consumption over the past one hundred years. The world energy consumption has been doubling every twelve years. Much of the energy consumed comes from fossil fuels such as coal, oil and natural gas. The world reserves of fossil fuels are limited. Unless other unknown reserves of fossil fuels are discovered in the near future (and this appears to be unlikely) there is a real danger of the

Due to rapid energy consumption, the existing fossil fuels will be depleted within a few centuries.

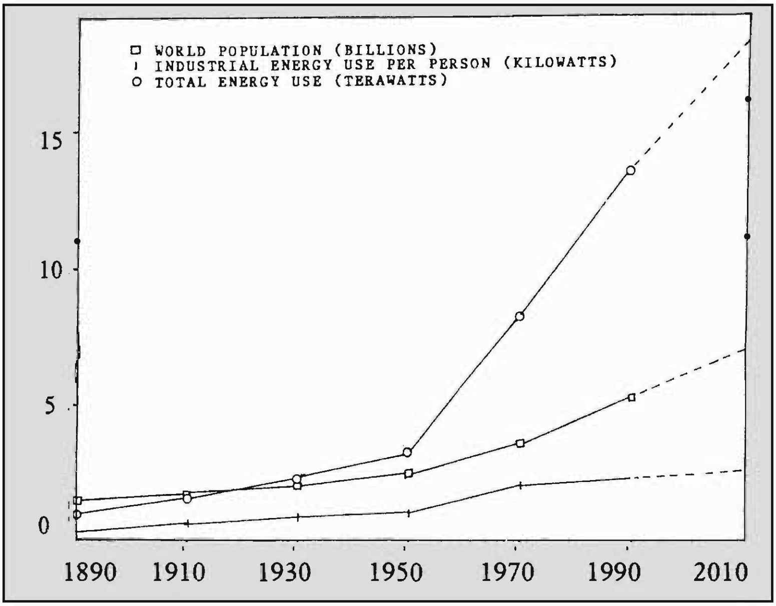

Figure 1. Variation of world population and per capita industrial energy consumption in the last 100 years. Note the rapid increase of total energy use since 1950.

existing reserves being exhausted in the next few centuries. It has been estimated that coal, petroleum and natural gas reserves are likely to be exhausted at the present rate of energy consumption by 2500, 2100 and 2020 AD respectively.

An unchecked use of fossil fuels has led to environmental pollution. It is only in recent years that awareness of the damage done by pollution is growing and legislation is being enacted in many countries to control pollution.

Among the alternate sources of energy, nuclear energy generated by fission of heavy elements like uranium is already being exploited by a few countries. However there is substantial world wide opposition to nuclear energy arising from the health hazards posed by accidental leakage of radioactive materials from a nuclear reactor. The problem of radio-active waste disposal also presents a serious argument against the use of nuclear energy.

In view of the above situation technologists have been looking at alternate sources of energy. These sources should (a) provide abundant amounts of energy to last for several thousand years at increasing levels of energy consumption and (b) be free from environmental and health hazards.

The earth receives 4.14×10^{15} kWH of solar energy per day.

Alternate Sources of Energy

There are many sources of energy other than fossil fuels and nuclear fission – water and wind energy, ocean thermal energy, biomass energy etc. All these sources of energy are ultimately derived from the sun's radiation and its interaction with the atmosphere, biosphere and the oceans of the earth. One may also directly convert the solar radiation to heat or electricity. It is therefore necessary to give some details about solar radiation and discuss its interaction with our atmosphere.

Solar Radiation

The energy radiated from the sun comes from thermonuclear reactions taking place in its interior. The sun radiates about 8.33×10^{24} kilo-watt-hours (kWH) of energy per day into space. Of this the earth, because of the small solid angle it subtends at the center of the sun, receives 4.14×10^{15} kWH per day. Ninety nine per cent of this energy is spread out over a range of wavelengths of the electromagnetic spectrum from

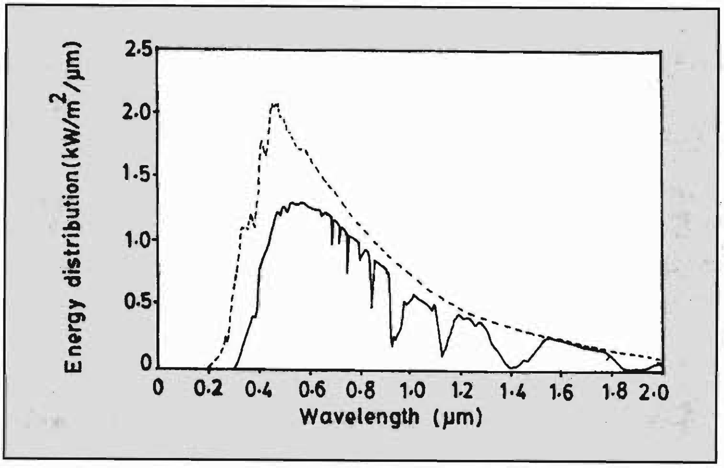

Figure 2. Spectrum of the solar radiation. The area between the dashed line and solid line represents the portion of sunlight absorbed by the earth's atmosphere.

Hydro-power is the most commonly used indirect method of converting solar energy to useful work or electricity.

2800 A° to 49,600 A° (1 A°=10^{-8} cm). The solar spectrum is shown in *Figure 2*. The maximum intensity of the radiation occurs at a wavelength around 5600 A°. The human eye is most sensitive in this wavelength region. The intensity falls off both in the infra-red region with wavelengths longer than 6000 A° and in the ultraviolet region with wavelengths shorter than 4000 A°.

Out of the total radiation received from the sun nearly 30% of it is reflected back into space, 47% is absorbed by the atmosphere, water and land mass of the earth and directly converted to heat, and the remaining 23% causes evaporation and movement of wind. A very tiny fraction of the radiation is utilized by the green plants for photosynthesis. Under special conditions, vegetable matter finds itself in a reducing atmosphere (atmosphere depleted in oxygen) which greatly retards its decay. The fossil fuels are the result of such retarded decay processes and they are also products of solar radiation.

Interaction between solar radiation and the earth's atmosphere

The earth's atmosphere has an important role to play. The solar radiation first meets with oxygen and ozone layers in the atmosphere at a height of 18 to 30 km. Ozone (O_3) and molecular oxygen (O_2) absorb the energetic short wavelength photons of the sun's radiation and dissociate into molecular and atomic oxygen. These species then react with other oxygen molecules to reform O_3 and O_2. Through such reactions the ozone layer changes the character and strength of the solar radiation passing through it.

On further penetration through the atmosphere, the solar radiation meets with other gas molecules and dust particles. Some of the photons in the radiation are scattered in all directions. Water molecules absorb strongly in the infra-red region.

In *Figure 2* the difference between the dashed curve and the continuous curve shows the effect of the interaction of solar radiation with the atmosphere. The intensity of the radiation reaching the earth's surface is also affected by the angle of incidence of the radiation. The larger this angle, the more is the thickness of the atmosphere through which the radiation travels before reaching the earth.

Wind currents caused by temperature differences between different parts of the earth can be used to generate energy.

Indirect Utilization of Solar Energy

Hydro-power: Water is evaporated by the heat from the sun and it later precipitates as rain. The rain feeds the rivers which run into the sea. The flowing water in the rivers can be used to generate electricity or turn water mills. Hydro-power is the most widely employed indirect technique for the conversion of solar energy into work or electricity. In developing countries one has not fully tapped the existing hydro-power potential. However hydro-electric projects cause large areas of land to be submerged and result in the displacement of a large section of the population at the site of a dam. There are also apprehensions that such large reservoirs of water can trigger seismic events. Because of these reasons there is some opposition to such projects.

Wind power: The sun heats up the land mass and oceans of the earth. However the heating is non-uniform due to the angle of incidence of the sun's radiation and the cloud cover. The differences in temperature in different regions lead to pressure differences in air. Convective currents of air are set up to equalize the pressure. One can set up wind mills to tap the kinetic energy of these air currents and convert the energy into electricity.

A resource survey was conducted in India in the early eighties. The data suggest that in West Rajasthan, West Gujarat, parts of Maharashtra, Karnataka, Andhra Pradesh and Tamil Nadu conditions are favourable for tapping energy from the wind. In other parts of the country the wind speed is too low to be exploited for the generation of energy.

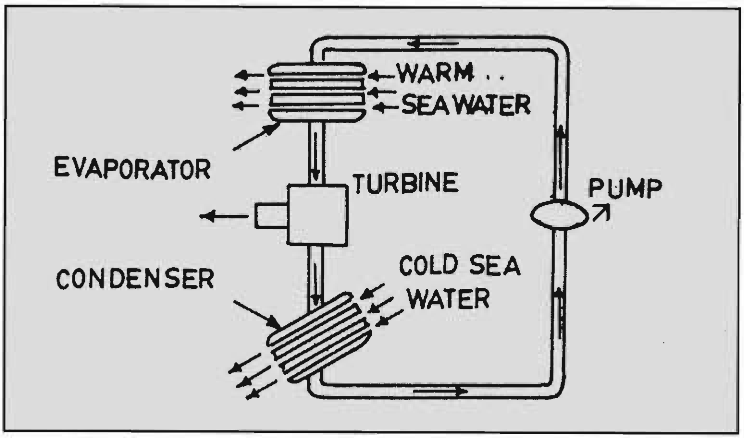

Figure 3. Operational diagram of an OTEC system. The working fluid is commonly ammonia or propane.

Ocean Thermal Energy: Seventy percent of the earth's surface is covered with water. Nearly 45% of the solar energy reaching the surface of the earth is absorbed by the surface layers of the ocean. The top layers of the ocean to a depth of 50 to 100 meters are considerably warmer than the deeper layers. One can operate a heat engine between the top of the ocean and the deeper layers to generate work. One such engine is depicted in *Figure 3*. A working fluid of low boiling point evaporates by absorbing heat when in thermal contact with the surface layers of the ocean. The vapour expands through a turbine setting it in motion and then condenses in a region deep in the ocean. It rejects heat at the lower temperature. This process can be carried out repeatedly in a closed cycle. One may also use an open cycle in which sea water itself is the working fluid. Such a heat engine is called the Ocean Thermal Energy Converter (OTEC). Although the temperature difference between the top and bottom layers of the ocean is small (a few degrees Celsius) one can achieve an efficiency of as much as 2% in converting the thermal to electrical energy. Since the thermal energy is available continuously and no fuel is burnt, the OTEC appears to be ecologically acceptable.

The surface layers of the ocean are at a higher temperature than the interior layers. One can employ a heat engine, operating between these two temperatures to generate electricity.

Biomass: Green plants have the unique capability of converting solar energy into chemical energy by the process of photosynthesis. They convert carbon dioxide and water into simple sugars in this process. This finally leads to biomass. Biomass is available over much of the earth's surface. The utilization of biomass will not add to carbon dioxide pollution. The most promising short term application for biomass powered gas turbines are in sugar cane and alcohol industries where large quantities of biomass residues are readily available. Gas turbines fueled by sugar cane residue will generate more electricity than what sugar cane and alcohol industries need!

Biomass produced by photosynthesis can be burned to run gas turbines.

In India the amount of biomass used in rural areas for cooking is comparable to, or even higher than, the consumption of coal. Biomass as a source of energy was neglected with the advent of fossil fuels and electricity. There is now a renewed public interest in obtaining energy from biomass.

Direct Conversion of Solar Energy into Heat

Solar heating, the direct conversion of solar energy into heat, has been in vogue for more than 2000 years. The technology of solar heating is well developed and solar heating devices operate at high efficiency. A solar heating system collects solar radiation, transfers it to a desired location and converts the radiation to a usable form for application. The main components of such a system are collectors, heat transfer liquid, piping, pumps and controls.

Solar energy can be directly converted to heat with a reasonably good efficiency.

The most popular collector used for space heating is the flat plate collector shown in some detail in *Figure 4*. The radiation

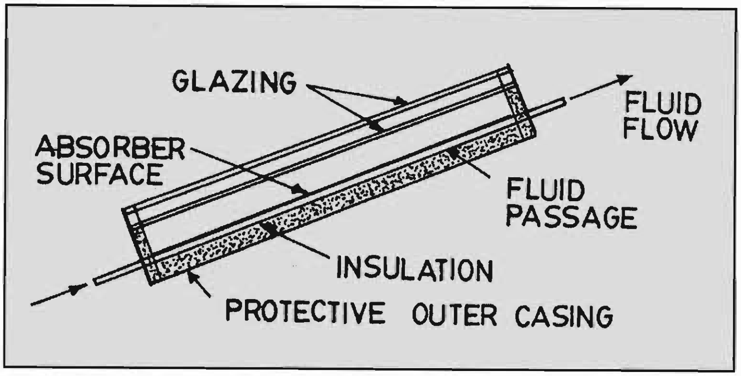

Figure 4. A flat plate solar collector.

is absorbed by the absorber surface which is in direct contact with a pipe through which the heat transfer fluid flows. The fluid is heated by the absorbed radiation. Water or water mixed with antifreeze solution is the most commonly used heat transfer liquid. For room heating applications, one may use air as the heat transfer fluid. The hot air is directly blown into the rooms to be warmed instead of being carried through tubes along the walls.

Cooking: Solar cookers have the advantage that they keep the environment clean. There are two types of solar cookers. In the first type the solar radiation is not concentrated. In the second type solar radiation collected over a large area is concentrated into a small volume. The temperature attained in the second case is much higher than in the first. The first type of solar cooker consists of a thermally insulated box with a transparent cover to allow the solar radiation to enter. The inside of the box is painted dull black. The solar radiation is absorbed and converted to heat. The plate cover does not allow the heat to escape. One can reach a temperature as high as 140°C with a suitably designed cooker. The second type of cooker uses a lens or a reflector to concentrate solar radiation.

Desalination: One can use the flat plate collector technology to convert brackish water to potable drinking water. The heat generated by solar radiation evaporates the brackish water. The evaporated water, free of salt, condenses on a colder surface and is collected.

Direct Conversion of Solar Energy to Electricity: The Photovoltaic Cell

Photovoltaic (PV) generation has the advantage that it is free of pollution. The systems are simple and need little maintenance. They are well suited for use in remote arid regions. There has been an increase in research efforts in PV cells in the last ten years, mainly to increase the efficiency of conversion, to reduce the cost of production, to prevent degradation of the system over a period of time, and to integrate and control a large number of such systems.

A PV or solar cell is a semiconducting p-n junction device. The junction is formed between a p (or hole) type semiconductor and a n (or electron) type semiconductor. The p and n regions are produced in the base semiconducting material like silicon by doping with suitable elements in specific concentrations. In such a device there is an excess of negatively charged acceptor atoms on the p side and positively charged donor atoms on the n side. This produces a space charge region near the junction. This space charge creates an in-built electric field at the junction. When a voltage V is applied across such a junction, the current I through the junction is given by

$$I_d = I_0 \left[\exp(eV/kT) - 1\right] \quad (1)$$

Here e is the magnitude of the electronic charge, k is the Boltzmann constant and T the absolute temperature. When V is negative i.e. in the reverse bias condition in which the p type is negatively biased relative to the n type, the current reaches a saturation value I_0. Smaller the current I_0 larger the energy band gap of the semiconductor. For silicon the band gap is about 1 electron volt (eV) while for germanium it is 0.7 eV. So I_0 is smaller for silicon than for germanium.

A photovoltaic cell consists of a p-n junction of a semiconductor. When light is incident electron-hole pairs are generated which diffuse to the two sides of the junction generating an open circuit voltage.

In a solar cell, shown in *Figure 5*, the junction is at a small depth from the surface. When the photons are absorbed near the surface they create electron-hole pairs near the junction.

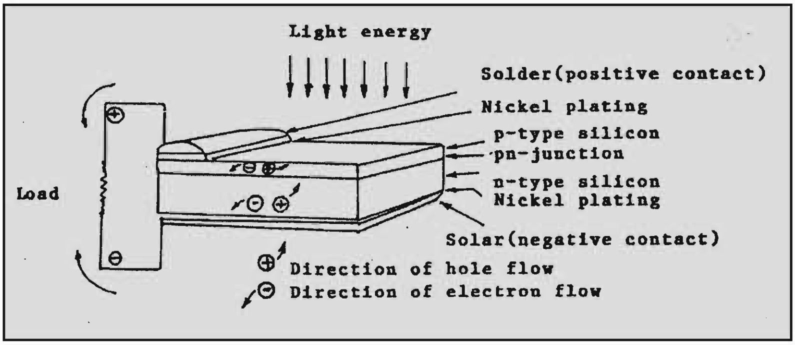

Figure 5. Basic diagram of a p-n junction photovoltaic system. The thickness is exaggerated for clarity.

Each photon of frequency ν carries an energy hν, where h is the Planck's constant. Only photons with energy larger than E_g, the band gap, can produce electron hole pairs by absorption of the photons. The holes created thus drift to the p side and electrons drift to the n side under the action of the in-built electric field at the junction. If η is the efficiency of collection of the electron hole pairs, the current I_s produced by the solar radiation is given by

$$I_s = N\eta e \tag{2}$$

where N is the number of photons absorbed in the material, each photon producing an electron-hole pair. This current is in the opposite direction to the diffusion current I_d. The net current is

The voltage generated at maximum power increases as the band gap increases.

$$I_{net} = I_s - I_d \tag{3}$$

If the solar cell is in open circuit then a voltage builds up across the cell. This open circuit voltage is given by setting I_{net} equal to zero and solving for the voltage. The open circuit voltage is given by

$$V_{OCS} = (kT/e)\ln\left[\,1+(I_s/I_0)\right] \tag{4}$$

If the circuit is closed by connecting a load resistance across the solar cell, a current flows through the load resistance delivering power. In a solar cell we need to derive maximum power at the load. The optimum load resistance R_{opt} for maximum power is given by

$$R_{opt} = [1+ (eV_{mp}/kT)]/(eI_s/kT) \tag{5}$$

where V_{mp} is the voltage developed across the cell when it delivers maximum power. V_{mp} increases as the band gap of the material increases. The maximum efficiency is given by

$$e_{max} = [x(x+1)]\,(V_{mp} I_s / P_{inc}) \qquad (6)$$

where $x = eV_{mp}/kT$ and P_{inc} is the incident radiant power.

The efficiency of a solar cell increases to start with as the band gap increases, reaches a maximum at a band gap of 1.5 eV and decreases as the energy band gap is increased further. Compound semiconductors such as $CuInSe_2$ and GaAs have a higher band gap than silicon or germanium and can yield higher efficiencies.

A photovoltaic system can be decomposed into solar cells, modules and arrays. The solar cell is the smallest unit of the PV system. Due to the small power generated by each individual solar cell, it is necessary to interconnect them in series and parallel patterns. This ensemble is called a photovoltaic module. These modules are then interconnected in series and parallel patterns in order to meet the electrical requirement of a specific load. This electricity can be used to supply power to an external load.

The maximum attainable efficiency of a solar cell is about 10%.

The efficiency of the total solar system is the product of the efficiencies of the individual components. Since the storage element is 50 to 80% efficient and the inverter is about 95% efficient, an array of photovoltaic cells with an efficiency of 10% will result in a solar system with an over-all efficiency of 5 to 8%.

The advantage of the PV system is that there is no limit on its size. It can be used at the site of energy consumption matching its size and distribution to the nature of energy consumption. Solar arrays can be mounted on the roofs of buildings and do not need additional land area.

A major drawback of terrestrial based photovoltaic generation is the interruption caused by inclement weather and the day-night cycle. This problem cannot be avoided anywhere on the earth. However, it is possible to have an electric photovoltaic power station in orbit in space which is free from such interruptions. The energy could be beamed from the space power station to the earth by a microwave link. Such an approach has the advantage that one can utilize the full strength of the solar radiation above the atmosphere for all the 24 hours in a day.

Thin film solar cells in contrast to solar cells of the bulk material will have the advantage of lower cost. However at present the efficiencies of the thin film cells are lower than the efficiencies of cells made of bulk materials. Further improvements in the efficiency of thin film cells are needed before they become competitive in the market.

Photo-electrochemical Conversion

Photo-electrochemical cells offer an alternate route for the direct conversion of solar energy to electricity.

Photo-electrochemical (PEC) cells use the junction between a semiconductor and an electrolyte to convert light into electrical energy. Most PEC devices are similar to the Schottky barrier solar cell, which has a junction between a metal and a semiconductor. In a PEC cell the metal layer is replaced by a highly conducting electrolyte. Equalization of the electro-chemical potential across the built-in potential barrier causes the formation of a depletion layer within the semiconductor and an oppositely charged layer in the electrolyte. The advantage of electrochemical cells is the ease of fabrication. In a PV cell the material of the optical window to be deposited on the semiconductor should have a lattice constant nearly equal to the lattice constant of the semiconductor. Such a stringent condition is not required for the PEC cell.

The photovoltaic program in India began in the mid-seventies as an R&D effort. In 1980, the development reached the stage of fabrication of solar cells and modules. During the sixth plan period a National Solar Photovoltaic energy demonstration program was started. Under this program the technology was scaled up to a level of a few megawatts per year.

Conclusion

India's energy requirements are considerable and growing. The urban population constituting nearly 20% of the total population consumes 80% of the total energy, while the rural population consumes the rest. In 1982 the Department of Non-Conventional Energy Sources (DNES) was established to develop renewable energy sources. The department is implementing various programs of research, development, demonstration and utilization of a number of renewable energy technologies. Devices such as community type biogas plants, solar water heating and cooking systems, solar photovoltaic pumps, wind mills etc. have had a good impact on the public.

Since the demand for energy varies from day to night and from time to time, while generation of energy usually takes place at a constant rate, there is a need to develop efficient energy storage systems. These systems will store the excess energy produced when generation exceeds demand and will release it when necessary.

Suggested Reading

- A A M Sayigh. *Solar Energy Engineering*. Academic Press. New York, 1977.
- Daniel Behrman. *Solar Energy –The awakening science*. Routledge and Kegal Paul Ltd.. London, 1979.
- Donald Rapp. *Solar Energy*. Prentice Hall. New Jersey, 1981.
- Furlan Rodriguez and Violini. *Non-conventional Energy Sources*. World Scientific. Singapore, 1985.

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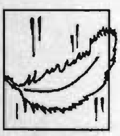

Success is the child of two very plain parents – punctuality and accuracy.

Longfellow