SOLAR ENERGY
THE BREAKTHROUGH FACTOR

Set the Way-Back Machine. Is It 1973?

Yet another installment of the relentless fossil fuel price hike soap-opera is now in progress. In lockstep with the rise in oil prices, the clamor for alternative sources of energy has also risen. Advocates of solar energy, hydrogen fuel, windmills, biomass and other forms of renewable power are again pressing their respective cases.

Political posturing on alternative energy issues is also in fashion again. Candidates and public officials of every persuasion speak in glittering generalities about a new era of renewable energy. Bureaucrats have been busy too. Demonstration program proposals and strategic energy policy documents are being generated at a pace not seen in a decade. Television specials on such topics as the greenhouse effect, acid rain and oil spills abound. The ususal suspects are trotting out energy concepts primarily designed to secure a piece of the energy research money pie, accomplishing little in the way of lasting progress towards solving the basic problem.

The more active among us have left chips, beer and boob-tube behind to attend environmental gatherings or to reinvigorate alternative energy associations, whose membership rosters were depleted during the intervening oil glut years of the eighties. A growing number of conferences and meetings provide a place to exchange views and ideas. Yet, running like a thread through all of these activities, there is an underlying frustration at being no closer to mass utilization of alternate forms of energy than the last time the oil barons turned off the spigot.

In Arizona, the solar option is only now being pulled out of mothballs. In spite of the state's prime geographic location and available land, it still has no large scale solar generating capacity. Contrast this with California, where 2 percent of that state's energy is generated by the sun in one form or another. Availability of specific alternatives has not even been properly defined. No clear and coherent plan exists for realizing popular aspirations to become "the solar energy state". Lack of leadership prevents implementation of needed reforms to the state energy policy and lack of funding prevents development of promising technology.

Sunny Skies, Blue Days

Harnessing the sun is no easy matter but two technologies have achieved some limited success. Both photovoltaic and solar thermal concepts have come a long way since the last oil crisis. While there are many other concepts and technologies available for capturing and storing solar power, a detailed consideration of them is well beyond the scope of this article. If you are interested in a survey of solar technology, <u>DIRECT USE OF THE SUN'S ENERGY</u> by Farrington Daniels is highly recommended. This book is exceptionally informative and well worth reading [1].

One of the keys to widespread utilization of solar energy is the efficient collection of sunlight and its conversion to a more useful form. Classical solar concepts have long sought to attain this goal by electronic and thermodynamic means. These two approaches seem to offer the best hope for achieving workable solar power systems. Photovoltaic technology is presently the front-runner in the race to develop a solar industry. This is partly because of the simplicity of the concept and the existence of a large and well organized semiconductor industry.

Solar cell technology is improving rapidly and the cost of the hardware is about one tenth what it was a decade ago [2]. Small scale applications such as solar powered cars are quite feasible, but don't rush over to your neighborhood car lot just yet. Suncars are not mass produced. Arizona State University recently built such a vehicle, the Sun Devil Crusier, for a meager $50,000 [3]. The University of Michigan spent a whopping $800,000 for its Sunrunner [4]. And even this sum pales to insignificance next to the capital outlay for the General Motors Sunraycer. This tour de force of mobile solar power is an 8 million dollar extravaganza that can attain a speed in excess of 80 MPH [5, 6]. The photovolatic array alone is valued at 2 million dollars.

Solar thermal (engine) technology has also improved. The tiny Ericsson Sun Motor astonished the world in 1883 by successfully converting solar energy into mechanical power [7]. Today, the LUZ solar thermal electric generating facility near Barstow California produces 80 megawatts of power, enough electricity for a small city of about 400,000 people [3]. Expansion of this solar power plant is underway and it will eventually provide enough electricity for a million people, ironically, a city roughly the size of Phoenix, Arizona.

Small scale solar thermal applications such as the 200 kilowatt Coolidge solar pump project are not economically justifiable using classical solar technology [8]. The large California solar power facility was only feasible because state law mandated that utilities purchase electricity generated there at peaking plant prices. Contrast that to Arizona, where utilities pay only base load prices for electricity generated by alternative energy powerplants.

If you have only recently become interested in solar energy, it may seem that an astonishing amount of progress that has been made. Those who have more than just a passing acquaintance with the technology are well aware of the lack of practical results, however. Part of the problem is the result of the low conversion efficiencies of both photovoltaic and solar thermal devices. The electronic and thermodynamic details of conversion losses are well known, and are too complex to discuss here. Regardless of the technical reasons for the losses, the fact remains that approximately 82 to 91 percent of the energy falling on a solar collector is wasted.

When large amounts of power are needed or when a mobile power source is desired, this power loss is a major factor. Solar collector costs are a large part of the expense for any solar installation. Add to this disadvantage the fact that, even for modest powerplants, large fixed installations of collectors are required. The power density of solar radiation reaching the earth's surface is roughly 1000 watts per square meter, assuming no losses other than normal atmospheric attenuation [2]. Further, This power level is only available for about 5 hours a day [9].

At best, only 90 to 180 watts per square meter are actually available with present solar collection and conversion technology. This value is usually smaller in practical solar installations. If 24 hour operation is contemplated, the collector must operate the power plant and recharge the storage unit. This further decreases the total power available at any given time to about 18 to 36 watts per square meter. This highly simplistic (and I might add somewhat optimistic) look at the physics of solar energy conversion should convince even the most ardent advocate that the realization of a practical and economical power plant is, at best, a very tough proposition.

An Electrifying Idea

There is never any shortage of problems when developing innovative new concepts. Although heavily discounted by many professional scientists and engineers, breakthrough inventions are a force to be reckoned with in overcoming barriers to technical development. The lessons of the past cannot be ignored. Practically every piece of modern technology was once considered impossible, and most of it had vocal skeptics.

Discontinuous technical advances in the "state-of-the-art" (breakthroughs) may occur at any time. Such innovation often occurs in places where it is not expected. More often than not, it is also originated by individuals who are believed not to have the knowledge or facilities needed to accomplish such feats. Over 60 percent of the major innovations in the 20th Century were produced by individual inventors working in small businesses [10], not large corporations where most of the funding goes.

Photovoltaic solar arrays have efficiencies that range from about 18 percent for crystalline silicon power cells to approximately half that amount for amorphous silicon arrays [2]. Gallium arsenide solar arrays can achieve roughly 22 percent conversion efficiency, but the cost is higher than silicon cells. While the effectiveness of available photovoltaic technology may be disappointing, a better method may have been discovered.

Development of more efficient solar cells does not depend entirely upon development of new semiconductor materials such as gallium arsenide and incremental improvement of conventional semiconductor fabrication techniques. There is no reason why a photovoltaic cell must be constructed exclusively from semiconductor material using bipolar junctions for accomplishing the photoelectric conversion process.

Microwave antenna arrays called rectennas can accomplish conversion of electromagnetic microwave energy to DC electrical power at efficiencies in excess of 80 percent [11]. Since light from the sun is part of the same electromagnetic spectrum as microwaves, it should be possible to adapt microwave techniques to produce antennas that receive visible light.

A specialized optical rectenna that operates on visible light rather than microwaves exists today [12]. This unique photoelectric unit is called a Lepcon [13]. It consists of multiple rows of submicron sized dipole antennas for receiving light waves. As solar photons strike the .5 micron Lepcon arrays, they are converted to DC electric power with a conversion efficiency of 75 percent. This efficiency is far in excess of anything even theoretically projected for semiconductor solar cells.

Three technical problems must be solved for these devices to become mainstream solar conversion products. First, each optical rectenna responds only to one wavelength. Sunlight is a combination of many different wavelengths. Second, the high frequencies at the optical end of the spectrum lead to extreme skin effects, that is, the tendency for electrical current to travel only on the outside of a conductor. And finally, fabrication of submicron rectennas will require sophisticated manufacturing technology.

Submicron (less than .000001 meter) electronic components are within reach of present day technology and will certainly be possible by the early 21st Century. Conventional electronic fabrication techniques are already approaching a level where quantum effects loom as a technical barrier [14]. At these levels, (less than .0000001 meter), a component with dimensions of .5 micron is large by comparison, so we are already at the point where manufacturing such devices is probable rather than merely possible.

Engines Of the 21st Century

Photovoltaic solar cells are not the only way to harness solar energy. Thermal engines have also achieved some success in this arena. Conventional solar thermal system engines have about the same efficiency range as ordinary semiconductor photovoltaic arrays, but for different reasons. These engines are not practical enough for small scale solar powerplants, however. The collector surface required for even a modest engine is enormous. What is needed is a powerful, extremely efficient solar heat engine that utilizes a collector surface small enough to be portable. Knowledgable individuals would be quick to point out the intrinsic impossibility of such a machine. Thermodynamics doesn't seem to offer even a theoretical means of achieving the objective. Or does it?

The primary technical barrier to developing a more efficient solar heat engine is usually assumed to be due to the effect of the second law of thermodynamics. This physical law limits conversion efficiencies of engines operating between given temperature ranges. All heat engines normally encountered operate between two temperatures, the source of heat that drives the engine and the sink where heat not converted by the engine is rejected.

As the range of the temperature differential between source and sink increases, the thermal efficiency of the engine also increases. Since many engines use the earth's ambient temperature as a heat sink, the temperature of the heat source must be as high above it as possible. That is the main reason why high temperatures are preferred over low temperatures in collectors intended to operate solar engines.

All heat engines operate according to a series of steps known as a cycle. A cycle is merely thermodynamic processes by which heat is converted into mechanical work. In 1824, Sadi Carnot, a young French artilleryman with an industrial background, wrote a landmark technical paper entitled "Reflections on the Motive Power of Heat". In this paper, he described heat engine operation in terms of a thermodynamic cycle.

A series of four thermal processes make up the Carnot cycle. They are: an adiabatic compression, an isothermal expansion, an adiabatic expansion and an isothermal compression. Those who are interested in finding out more about this cycle should obtain a copy of “HEAT ENGINES - THERMODYNAMICS IN THEORY AND PRACTICE” by John F. Sandfort [15]. This book offers a clear, non-mathematical presentation of thermodynamics as well as an interesting historical account of progress in engine technology.

Certain types of engines are considered impossible. Machines that produce more energy than they consume violate the first law of thermodynamics. An engine of this kind would produce work with no external source of heat. A device operating in this way would belong to a class of machines called perpetual motion machines of the first kind.

An engine that operates with an efficiency of 100 percent, converting into work all heat supplied to it, is believed to violate the second law of thermodynamics and is an example of a perpetual motion machine of the second kind. Although it does not violate the first law, such an engine does not reject heat to a second, lower temperature.

Even an engine operating between an arbitrary temperature and absolute zero would produce some heat as a result of friction. A portion of this heat would be unavailable to the engine for conversion. Without a heat sink in the form of a second lower temperature, the engine could not reject this heat and would cease operating.

The Kelvin-Planck formulation of the second law implies that a cyclic heat engine can not convert heat transferred from a single heat reservoir into an equivilant amount of work as its sole external effect. For this reason, classical interpretations of the second law have always assumed that it is impossible to construct, even in principle, a cyclic heat powerplant using a single thermal reservoir.

There is something unusual about the behavior of water. Unlike almost every other substance, it is less dense when frozen than when it is liquid. In simpler terms, an ice cube will float in liquid water. If a given volume of water is cooled, it becomes more and more dense (its volume decreases) until, at 4 degrees Centigrade, it reaches maximum density. As the temperature is lowered still further, the density decreases (the volume increases). This anomalous behavior makes possible a thermodynamic cycle so bizarre that it alters, forever, our concept of heat engines and the limits to their performance.

Quoting from an article in the American Journal of Physics [16]:

> Sommerfield has given an apparent case of a perpetual motion machine of the second kind. This consists of a Carnot engine employing liquid water and operating between the normal and anomalous regions of thermal expansion. Somerfield's paradox is resolved by showing that (it is) a Carnot cycle... (which) involves expansions for both isothermal processes.

According to Bejan [17]:

> One interesting consequence of the anomalous behavior of cold water is that the reversible and adiabatic lines are cup shaped. The Carnot cycle then consists of only two processes, a reversible and adiabatic volume change connected to a reversible and isothermal volume change.
>
> If the sense of the cycle is as indicated... then during the first part of the reversible and isothermal expansion process, the system absorbs heat from the lone heat reservoir. During the second part of the process, a heat transfer interaction of exactly the same magnitude as the first occurs in the opposite direction.
>
> We have an example of a heat engine cycle that proceeds while in contact with only one heat reservoir. Furthermore, at the end of each

> cycle, the net effect is not the emission of heat transfer by the reservior that serves as the heat source.

But it is Truesdell [18] who best describes the true implications of this strange Carnot cycle:

> The coefficient of performance of the cycle we are discussing is infinite. At no expense of work or heat, a body may expand and contract forever. All work needed to effect one isothermal part of the cycle is given back in the next. The adiabatic part of the cycle, at the will of him who starts the engine, can be either an expansion or contraction; whichever be selected, the adiabatic part of the cycle first cools the working body and then warms it. Any ideal machine which functions with no losses can serve as the basis of a real machine which functions with scant losses.

The Sommerfield paradox describes nothing less than a thermodynamic cycle operating from a single heat source, something almost universally dismissed as theoretically “impossible”. Although Bejan notes that modern thermodynamics must question the equivalency of all formulations of the second law, he observes that the Kelvin-Planck statement of the second law is not violated in this case. Referring to widespread misinterpretation of the Kelvin-Planck statement of the second law, Professor Truesdell admonishes authors to exercise care in their work [19]:

> It is one thing for a textbook to leave anomalous behavior out of account because it is untypical of the circumstances most engineers encounter; it is quite another when a mathematician presents as axioms for the whole science of thermodynamics statements that in fact fail to apply to one of the two most useful substances on earth, essential to the existence of life.

For those who are seeking an improved solar engine, the fact that such an unusual thermodynamic cycle exists at all removes certain theoretical and conceptual barriers. It also shows the value of a heuristic approach to innovation.

Because the previously noted thermodynamic cycle uses liquid water, a practical engineer might conclude that a real machine could not be constructed. That line of reasoning is brought into question as a consequence of the liquid engine constructed by John Malone in 1931 [7]. Producing about 45 horsepower at 180 rpm, the unit operated on a Stirling power cycle using liquid water as the working fluid. There is no theoretical reason why a modern liquid engine could not be constructed using a monothermal Carnot cycle.

Like Carnot's original creation, the cycle described by Truesdell and the others is more important as a means of envisioning thermodynamic ideas than as a practical engine. Once a technical impasse is breached, there is at first a trickle of information, than a rivulet of knowledge and finally, a torrent of application as the old barriers come down. With the dawning of the 21st Century, it is absurd to think that the science of thermodynamics will not evolve further. The knowledge that more efficient heat engines are possible will inevitably lead to their discovery.

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