

Solar Thermoelectric Technology: Part 1

The Relative Merits of Thermoelectric Generation and Storage

by Dennis L Feucht

Several decades ago, Jay Forrester, the MIT inventor of magnetic core memory, did a global dynamics simulation involving a system of nonlinear differential equations. It predicted the demise of civilization as we know it due to energy depletion, overpopulation, and overpollution. A similar study funded by the global-elite group, the Club of Rome, corroborated his simulation and reported doom in a widely-read book in the 1970s, *Limits to Growth* by Dennis Meadows. While the conclusion that we would be out of energy by now and the end would be near has not been realized, the general direction of these simulations cannot be brushed aside too hastily. Few places on earth are left that petroleum engineers and geophysicists have not explored to satisfy the increasing demand for oil. Global oil production is predicted to equal demand this decade, and more precisely, the crossover is occurring about now.

With a diminishing supply of oil, and at a time when the most populous part of the developing world is expanding economically, it is not hard to conclude that the search for new energy sources beyond oil should be a high engineering priority. There is, in fact, plenty of available energy but it is underused due to lack of efficient technology. The sun provides an energy density of about 1 kW/m^2 when overhead on a clear day. How might it be converted to electricity?

Solar Energy: Three Alternatives

Three alternative solutions for the use of solar energy are:

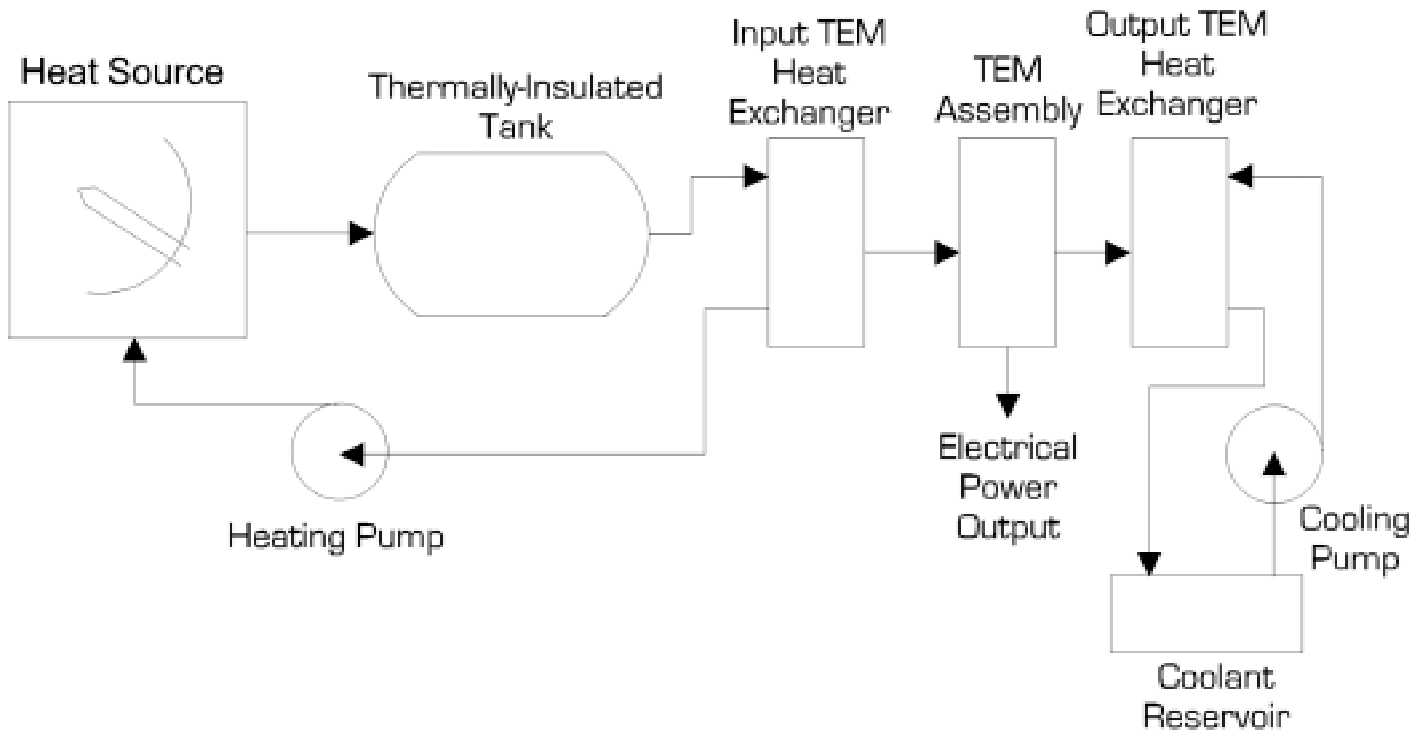
1. **Photosynthesis:** grow crops that can either be burned directly to power a heat engine (such as a steam turbine) and turn a generator, or produce biofuel which can be stored, transported, and burned, or used in fuel cells
2. **Solar Photovoltaic (PV):** use solar PV panels to convert sunlight to electricity and store it in batteries
3. **Solar Thermal:** concentrate solar radiation with a collector, heat a fluid, store it in an insulated tank, and drive a thermoelectric converter

Photosynthesis currently leads the other approaches by a wide margin, as biomass is burned to provide energy in the developing world. Some countries, such as Brazil, are making a significant effort to change from hydrocarbon to ethanol fuel. In the developed world, crops are being grown and converted to biofuels such as ethanol, which can be used to power the emerging direct-alcohol fuel cells. But, for now, solar panels are the dominant attention-getter among alternative-energy enthusiasts. The under \$1/W panels, competitive with the power utility grid, were supposed to be here by now. The low-cost technology abandons semiconductor batch processing of solar-cell wafers in favor of extruding a continuous-process ribbon of thin-film amorphous material. The ribbon is chopped into panels and used as roofing material. But new technology development, as we know, is a nontrivial affair. Solar panels are still an expensive \$3.50/W years after the forecasts touted cheap PVs.

Solar Thermoelectric System

The problem of electrical supply can be decomposed into two problems: energy *generation* and *storage*. With electric output from solar panels, charge must be stored in batteries. This is expensive and cumbersome. It is the *storage* problem that leads to a major advantage of the third alternative, solar thermal.

A block diagram of a solar thermoelectric system (STES) is shown below:



TE Conversion

The converter in the above diagram is a *thermoelectric module* (TEM) assembly. More generally this is some kind of thermoelectric conversion device which converts a temperature differential, ΔT , to electric power, as heat flows from hot to cold side through it. TEMs are commonly found in car coolers and consist of tens of thermocouples in series. Thermocouples transfer heat by the mechanism of electron diffusion. This is not an efficient process but the efficiency has been increasing as the figure of merit, a quantity denoted by Z , increases. One company, Hi-Z, in San Diego, California (<http://www.hi-z.com>) offers TEMs optimized for electricity generation, with a specified efficiency of 4.5 %. This is about 4% worse-case over the ΔT operating range of the STES. To maintain efficiency, the cold side is held at T_L by a cooling loop using fluid-cooled heat sinks, a small pump, and cooling pond or radiator and fan. The price of TEMs (from Hi-Z) runs around \$7.71/W, over twice that of \$3.50/W PV panels. For a TE system sizing of 400 W average and peak, the cost of the TEMs is US\$3084.

Solar Thermal Collection

A concentrated solar collector is required to achieve the desired operating temperature (275°C) of the thermoelectric converter. Three possible collectors are:

Dish: tracks sun in two dimensions with heat collector at the focus of the paraboloid

Trough: parabolic trough with linear pipe at its focus tracks sun

Heliostat Array: multiple mirrors track sun in 2-D and focus on fixed heat receiver

Of these three alternatives, the heliostats allow the heat collection to be at the tank, thereby avoiding the need for flexible tubing and a high-temperature pump. However, each of the dozen or so mirrors requires two motors and controls for 2-D solar tracking. This solution is not minimal. The dish has temporary appeal

because so many surplus microwave dishes are available, as fiber-optic cable replaces telecom microwave links, and large C-band satellite dishes are replaced with smaller ones. The dish surface is covered with low-cost metalized plastic sheeting.

The optimal solution to me appears to be the heliostats, though the trough is a competitor. It too can be constructed with metalized plastic sheeting and with proper orientation, tracking need only be one-dimensional. The collected thermal energy is stored as a fluid in an insulated tank.

A 400 W average power output requires a thermal input power, or heat rate, of 10 kW for 4% TEMs. This roughly corresponds to a dish of 12 feet diameter, or 10.5 m² area, a common surplus microwave repeater dish size. (As microwave links are torn down, telecom companies are giving these dishes away for the hauling.) However, the duty-ratio for the sun is about 25% (when dark skies and seasonal variations are included), increasing collector sizing by 4 times, to 40 kW, or 4 12-foot dishes. A parabolic trough of 10 m² area has dimensions of 1.6 m (5.3 ft) × 6.3 m (21 ft).

A 10 m² concentrating collector using metalized plastic sheeting for reflecting material can be constructed using low-cost building materials for around US\$1500. By using a parabolic trough and 1-D solar tracking, the pipe at the focal line can remain fixed to the storage tank, avoiding the need for high-temperature flexible tubing.

Solar Thermal Storage

Consider the significant cost advantage of thermal versus electrochemical (battery) energy storage. Suppose a fluid with the density and heat capacity of water (4.187 kJ/kg·K) were stored in a 1 m³ tank with R-20 insulation at an average storage temperature of 250°C. (A spherical tank of 1000 liters, with R-20 thermal insulation, results in a 6°C/day loss of temperature, which is 300 W of continuous loss.) The tank has a diameter of 1.24 m (4.0 ft), the size of a household appliance. The stored energy, useable over 100°C, is:

$$Q = \left(4.187 \frac{\text{kJ}}{\text{kg} \cdot \text{K}} \right) \cdot \left(1 \frac{\text{kg}}{\text{l}} \right) \cdot (1 \text{ kl}) \cdot (100 \text{ K}) = 419 \text{ MJ} = 116 \text{ kW} \cdot \text{h},$$

assuming a worst-case ambient temperature of 50°C. An insulated tank of this size would cost around US\$200 with mounting and plumbed ports.

At 250°C the working fluid in the heating and storage loop cannot be liquid water. A sodium-potassium alloy is a possibility. So are some high-temperature synthetic oils. Additionally, fluid properties for heat transport can be optimized by using a different storage material in the tank optimized to store heat. The available energy of a substance due to its differential temperature above ambient is the *sensible* heat, because it can be "sensed" by measuring its temperature. A substance that undergoes a state change also changes internal energy to change molecular reconfiguration. This *latent* heat can be substantial. (This is why snow on roads is plowed instead of melted.) A material that is optimized for storing latent heat is a *state-change material* (STM). Suppose that the cost of the fluid and the optionally-additional STM is about 50% of the tank cost. Then the total heat storage system cost is about US\$300. Because the tank volume is not large, a slightly larger tank using a lower-performance fluid or STM is an attractive cost tradeoff.

Solar Thermal And PV Costs Compared

The TE approach succeeds based on the assumption that solar energy collection and storage is relatively cheap, thereby supporting inefficient TEM generation. Output power is dc and requires an inverter, but those are low-cost commodity items (even the better sine-wave ones are affordable, though not yet cheap) and are not a major factor in STES feasibility. Solar PV also requires an inverter.

The output-referred energy storage for the above 400 W system is 5.22 kW-h. At 400 W average output, it will last 13 hours, or about a half a day. Add US\$320 for the cooling loop, and the total cost of the 400 W, 5 kW-h STES is about US\$5,200.

For comparable energy storage in a battery bank, the output energies must be compared. The size of the battery bank, using 12 V, 50 A-h (600 W-h) deep-cycle batteries at US\$75 each, has 9 batteries and costs US\$675, or about twice as much for storage. When battery-bank replacement is considered -- perhaps every 10 years -- the 20-year cost is over 4 times. In addition, the batteries require somewhat more maintenance than a thermal storage system.

The lower cost of solar thermal collectors over PV panels is negated by the high cost of TEMs. For a 400 W PV system, the input power need only be $400 \text{ W} \div 0.25$, or 1600 W, assuming no battery charger loss. The PV panel cost, with tracker (to get 0.25 availability), is about US\$6400, resulting in a total PV comparison cost of US\$7100, or US\$1900 (27%) more than the STES. When the system is scaled up to 1 kW output, the advantage of the STES grows to 37%.

Closure

The STES mechanical (moving) components are heliostat motors, a small pump, and possibly a cooling fan. The PV system has only the panel tracking. The two are roughly comparable in the amount of maintenance. Why, then, with the lower cost of the STES, has it not become the preferred supply solution? The answer is that high-Z TEMs are only now becoming commercially available. Perhaps another reason is that alternative-energy distributors are familiar with PVs and do not yet know about STESs because they are not yet commercially available for distribution.

Part 2 will look at the critical subsystem, thermoelectric generation, in more detail and describes a new kind of TE device that has a measured prototype efficiency of 15%.

