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LAWRENCE LIVERMORE LABORATORY

University of California/Livermore, California

On the Economics of Thermodynamic Solar Power Systems

I. The Efficiency Function

L. F. Wouters

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ON THE ECONOMICS OF THERMODYNAMIC SOLAR POWER SYSTEMS

I. The Efficiency Function

The "Energy Crisis" has spawned a rash of proposals for "Using the Sun's Energy". These schemes generally involve significant extrapolations of modern established technologies, such that their economic analyses find a frail basis, and may even be somewhat suspect. In view of the evident need for some sort of framework for assessing these propositions, one can well ask if there are some relevant, basic, economic indicators. A mere expression of \$/kw or mils/kwhr does not always convey the complete situation.

In seeking central power systems having early applicational viability, some Solar participants have turned towards thermodynamic schemes. Photovoltaic and more exotic concepts (like photosynthesis) are seen as several technological generations down the road. The TD schemes universally involve an extensive thermal sub-system (which collects the Solar flux and delivers its energy as heat) coupled to a central thermodynamic sub-system (which converts the heat to work). Various degrees and models of storage may be invoked to supply power beyond the mere Solar day, in time.

The various Solar collector field concepts exhibit estimated capital costs running over a factor of three: \$900 to \$2500 per kw. The central plant equipment includes heat exchangers, turbo-generators, pumps, and other TD machinery, at \$50 to \$150 per kw; storage schemes reflect \$50 to \$200 per kw. Totals then run in the range of \$1000 to \$3000 per kw.

Compared to conventional power plants, this appears discouragingly high, even after folding in the cost of fuel on an amortized basis:

Conventional Power:	12 mils/kwh	(at \$3.50/BBL)
Solar Power:	22 mils/kwh	(at \$1000/kw)

However, one can hazard this question: In the Solar costs, are we not really seeing the full and timely consequences of a major cost inflation in technology across-the-board, rather than a domain-local effect? Conventional systems economics carries with it a heritage of development and fabrication capabilities capitalized at much lower dollar levels.

The central economic feature in the Solar thermodynamics business is evidently going to be the collector field. All system development and fabrication estimates reflect this. There are complex feasibility inter-relationships between collector configuration and TD loop design, but to first order, we can set aside the central facility at least with respect to its own cost sensitivity, per se. We permit a choice of TD configuration which first minimizes collector cost. In such a systems philosophy, an expensive turbine design may reflect as a more cost-effective overall system, for example.

At present, a projected collector cost of $\sim$ \$1000 per kw probably represents a threshold in speculative commercial attractiveness. What can \$1000 buy in the industrial market? A traditional guideline for product-process costs 10 to 15 years ago was this:

10¢ per lb	for the cheapest refined materials
\$1. per lb	for mass-produced fabrications
\$10. per lb	for sophisticated hardware

The mass-produced fabrications price has held surprisingly well. Detroit still makes 5000 lb vehicles for \$5000, but they are austere at that price.

Of course such numbers include a mixture of pro rata contributions: Besides the material cost per se, there are the shaping and finishing, the structural components, the environmental preparation. Their validity as "mean predicators", rests on the point that in a competitive society, cost-benefit influences operate broadly towards parity between product domains as well as within such domains.

The elements in a Solar collector field generally involve fabrications and installations noticeably more cultured than is characterized by "cheapest materials". Yet severe austerity is mandatory. Let us test a "price density" of 50¢ per lb; at least that will provide an economic reference point.

How much collector do we need for one kw ? Ideally, the Solar flux delivers this in 2 sq meters (High Noon in Arizona) but there are many inefficiencies between collector and busbar. Thus, at 50% thermal efficiency and 10% overall efficiency, we need 40 m², or about 400 sq ft to supply the kilowatt. That translates to ~ \$2.50 per sq ft as the permissible cost allocation to that charitable collector assumption.

Suppose that most of this goes into material purchase and processing. It means that we can buy a collector which weighs roughly $\frac{2.50}{.50} = 5.-$ pounds per sq ft. Anything weighing much more than this is in trouble, cost-wise. Relating this to the densities of typical fabrication materials we can also set a rough limit on the total allowable material thicknesses:

	<u>Density</u>	<u>Thickness</u>
Plastics	95 lbs/ft ³	5/8 inch
Glass	190 lbs/ft ³	5/16 inch
Steel	500 lbs/ft ³	1/8 inch

These are quite small material quantities; if the allowable area cost is \$1. per sq ft (for instance, @ lower efficiencies) and the allotted thickness must be distributed over several layers, they become almost diaphanous.

There is a related issue - that of "free" materials - like air, water, some "earths" perhaps. It deserves a bit of parochial history, since we are learning here (the hard way) that these aren't really "free" either. As a point of fundamental principle, one can argue that the materials fraction (in numbers above) is a minor part of the cost (less than 50%). The so-called "free" materials still entrain a commensurate degree of "Not free" manipulations for commensurate product sophistications.

The purpose of a Solar scheme is to make useful energy out of the Solar flux; it is not to "sell" mirrors, or PV cells, or flat plates, as the "best" way to use that thin allowance. Candidate concepts should be evaluated more by economic performance - by an "effectiveness" scale - than by any particular physical representation.

In order to generate such a composite effectiveness description within some loosely defined domain of TD schemes, I must take some liberties with representational and numerical exactness in characterizing each one. Hence there will be a "candidate bandwidth" to whatever analytic characterizations may be invoked. Furthermore, in these considerations I divorce the system model from any particular associations with rocks, water, glass, etc. I take the view that we'll pick whatever common-place embodiment comes nearest to working acceptably in the chosen design domain and also in "taking the heat". These arguments are nevertheless addressed to a class of system concepts figuratively put together using today's readily available, quantity commercial materials and processes.

I have not distinguished as yet between concentrating collectors ("mirrors") and non-concentrating collectors ("flat plates"). There is no particular economic indulgence granted to one or the other; both have to conform to the same constraints. As one basis for those concept choices, it was our judgment that the non-passive steering mechanisms involved in mirror schemes, imposed a sophistication which could not possibly meet the pertinent economic limitations, even on an area pro-rata basis. Accordingly we have addressed our considerations so far, almost entirely to static non-concentrating schemes. That does place an added burden on the balance between flux interception and thermal retention; the collector covers have to provide a perceptible, recoverable, thermal residue, yet be cheap.

In such a context, our first thermodynamic sally here at LLL, was the Greenhouse - an "air-breather" - which was aimed in the domain of 250°C to 300°C as the Carnot temperature. That easily generated too long a list of technical issues. Our second learning exercise is the Shallow Pond, which operates at ~ 100°C. It is in the process of also generating a surprisingly long list of questions - although we had to go deeper into the design issues before we encountered this resistance. The interesting thing is that the thinking of other Solar groups is converging towards very similar Thermal-TD concepts, as they too face practicality and the realities of economics.

This conceptual course is furnishing some useful effectiveness data points; these I functionally (and rudely) relate by this overall efficiency:

$$\eta = \eta_c \eta_{td} \eta_x = (\eta_p - \eta_n) \left(\frac{T_1 - T_2}{T_1} \right)' \eta_t \eta_x$$

in which:

η_c is the thermal efficiency of the collector

η_{td} is the overall thermodynamic efficiency

η_x collects a number of near-unity multipliers

η_p is the photon capture efficiency (temperature insensitive)

η_n is the thermal leakage efficiency $\eta_n = \frac{k_n}{\phi} (T_1 - T_2)$

η_t is the turbine efficiency

The prime calls attention to "enthalpic" temperatures in that term.

The collector efficiency (η_c) is very sensitive to perennial insolation undulations, and to the collector cover design (blanket, mattress, pillow, - - -) - in particular to the number of transparent sheets or layers and to their optical/spectral qualities. A casual inspection of its two competing components ($\eta_p - \eta_n$) suggests that η_c decreases sharply with increasing collector temperature (T_1); the "best-case" η_c function (depicted in Fig. 1) shows how severe an effect this is. But we know that thermodynamic efficiency (η_{td}) rises with T_1 , and this interesting competition is also depicted in Fig. 1. Finally the product of the three main efficiency components - the overall efficiency η - is plotted there as a "range band" of likely values. It is a comparative representation applicable to most flat-plate TD schemes (using contemporary materials and processes), provided that we accept first-place precision; the loci in both exhibits (Figs. 1 and 2) really represent central curves within probable value bandwidths of $\sim 30\%$. (That would clutter up these "dense" figures even more !)

The spectacular feature is, of course, the unmistakable broad maximum in that efficiency product somewhere around 150°C . The consequence of "better" mass-produced materials, would be to shift that peak (and the right-side droop) upward along the dashed extension in Fig. 1.

The various depicted functions are roughly normalized to our two conceptual experiences, and also to OTG concepts. In this latter case, the TD consequences of the low ΔT completely overwhelm any other considerations. (Like the point that it isn't a really analogous "Solar" scheme.) Even with more precise analytic definition, these curves will always be bands, because they would then represent the probable performance distributions of candidate systems in likely geographies. It would be useful to calculate and price a new system concept at an intermediate temperature. The position taken here is that the efficiency function still dominates the cost per unit output.

Figure 2 examines the contributions to the collector efficiency in more detail: The photon capture efficiency η_p , the leakage efficiency η_n , and again $\eta_c = \eta_p - \eta_n(T)$, all now as functions of the number of transparent cover sheets or layers n . Collector temperature appears parametrically for η_n (dashed curves) and for η_c (barred curves); η_p is insensitive to temperature. For a particular collector design temperature, there is a cover design knee or peak (in η_c), beyond which "more sheets don't help":

$$\left(\frac{\partial \eta_n}{\partial n}\right)_T \approx \frac{\partial \eta_p}{\partial n}$$

This is the basis for the broad "best case" curve (η'_c). (That also translates to the η_c locus in Fig. 1.) It well illustrates the competition between η_p and η_n , and the sharp way in which $(\eta_p - \eta_n)$ "shuts off the Sun", as one tries to achieve higher working temperatures.

For the purposes of these arguments, η_p was calculated as the direct Solar flux for the equinoctial mid-day in Arizona (33° latitude). This term must necessarily include climatic and ephemerical effects, because there is no other analytic to realistically account for these - and the consequences are substantial: At the Summer solstice, the overall efficiency may be 30% higher; at the Winter solstice, it may be near zero. η_p also includes the cumulative, angle-sensitive effect of Fresnel reflection at each interface, and the small, but finite, departure of the various materials from "perfect" optical behavior. So these effects also constitute a "band-width" generator (although not so represented in this particular exercise). η_n includes conduction, convection, and radiation losses; it is surprisingly linear with temperature difference in this regime (for a given n). Both terms are sensitive to the assumed optical - I.R. properties of the cover sheets. For these calculations, I assigned an I.R. emissivity of .5 to these sheets, corresponding to a "mediocre black-body" assumption. The outcome is not severely affected by a higher b.b. value (like .9).

Overall, the striking implication is that, using such run of the mill resources, one can only put together shockingly inefficient systems. Perhaps one can reach 3%. Whether that is dollar-economic, depends principally on how cheaply such low-grade systems can be contrived, and perhaps to some extent, on small expectable improvements. Thus far, it does seem that high-efficiency Solar thermodynamic plants require the evolution of a new generation of mass-produced materials and large-scale fabrication processes. That may not be as demanding as it sounds, because the synergistics among available materials and processes have hardly been explored with a Solar goal in mind.

One can turn the issues around to examine where the advancements are most likely to be. Evidently in something like this, a modest idea with high leverage, may be much more impacting than a brilliant idea with low leverages. Here is a good place to ask what the Greenhouse was all about, in the light of these gloomy conclusions. For one thing, the Greenhouse wasn't very good unless one could come up with a cheap way to produce glass with an emissivity of .1 or less in the I.R., and an anti-reflective coating, as well. (Note the box at upper right-hand corner - Fig. 1 - the "Super-Greenhouse".)

An advanced industrial mass process of particular Solar merit, would then be one which produces an inexpensive, strong, transparent, durable, high-temperature, sheet material - most likely a glass - having a high I.R. reflectivity and suppressed Fresnel reflection in the visible region. Such a cheap "Solar glass" would also significantly and favorably operate on η_{TD} , as it would permit a higher T_1 and better turbines.

Fig. 1 Achievable efficiencies

Note ordinate X 10 for Total Efficiency η
(Optimum n values implicit)

Fig. 2 Efficiency contributions

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