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On the Economics of Thermodynamic Solar Power Systems

II. The Turbine Trade-off

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ON THE ECONOMICS OF THERMODYNAMIC SOLAR POWER SYSTEMS

II. The Turbine Trade-off

In the course of discussions, I have sometimes indicated that a more expensive, higher efficiency thermodynamic sub-system could result in a less-expensive, more "cost-effective" Solar power system, overall. It is interesting to see how severe a trade-off this really is.

Let me construct a primitive two-component system model consisting of (1) the collector and (2) the turbine. Of course there are lots of other pieces between and around these items, but these two are the ones to which most "cost leverages" can be associated, in some way. A given collector design is assumed, having a defined specific efficiency and unit area cost. I vary the turbine efficiency parametrically from a reference value, and obtain an allowable cost trade-off as a ratio to reference turbine price. No attempt is made to relate a particular cost change to a particular design change - I only establish the maximum that one can afford to pay for any and all changes.

Let: D_o be the reference total cost

D_c - the collector fixed cost

D_t - the reference turbine cost

η_o - the reference turbine efficiency

Also $\rho_o = \frac{D_c}{D_t}$ the reference component cost ratio

Then $D_o = D_c + D_t = D_c (1 + \frac{1}{\rho_o})$

Primes identify variables belonging to a second, comparative, trial system, using a modified turbine of efficiency η :

$D_o \rightarrow D_o'$ $D_t \rightarrow D_t'$

$D_o' = \frac{\eta_o}{\eta} D_c + D_t'$

inasmuch as a different turbine efficiency imposes a first-order requirement for a different collection area by that ratio (for the same power output).

Write $R = D_t'/D_t$ $r = \frac{\eta}{\eta_o}$

Then $D_o' = D_c (\frac{1}{r} + \frac{R}{\rho_o})$

By the cost criterion: $D_o' \leq D_o$

so that:

$$\underline{(\frac{1}{r} + \frac{R}{\rho_o}) \leq (1 + \frac{1}{\rho_o})}$$

R is factor that clearly starts at unity; it expresses whatever added cost a "better" design involves, as a multiplier.

For sake of demonstration, I consider the limiting case in which these expressions are equal (max. cost case):

Find:

$$R = 1 + \left(1 - \frac{1}{r}\right)\rho_o$$

A simple way to exhibit the strong sensitivity of this trade-off is to consider the derivative:

$$\frac{\partial R}{\partial r} = \frac{\rho_o}{r^2}$$

In the reference vicinity: $\left(\frac{\partial R}{\partial r}\right)_o \approx \rho_o$

$$\text{Also: } \left(\frac{\partial R}{\partial \eta}\right)_o \approx \frac{\rho_o}{\eta_o}$$

In typical costed cases, ρ_o is a number like 20. (D_C @ \$1000/KW, D_T @ \$50/KW)
 η_o is typically .7, whence

$$\left(\frac{\partial R}{\partial \eta}\right)_o \approx 30$$

Putting it another way, one can afford a 30% increase in turbine price, to gain just 1% in its efficiency.

As another illustration, if the reference design (at \$50/KW) is a 60% machine, how much more can we afford for an 80% turbine ? (Same ρ_o) Find $R = 6$! It's a dead-even trade-off at \$300/KW simply on account of the savings in collector area (and cost). Of course one may choose to spend some fraction of that extra \$250/KW on some other improvement peripheral to the turbine itself, which makes it behave more efficiently. And of course, one would prefer not to spend it all.

These numbers also point to the strong penalty one would pay with less efficient, slightly cheaper machines. Thus, a turbine specification should place efficiency first and machine price second, rather in contrast to conventional power plant arithmetic, and the force of the argument should be understood by the designer and the fabricator.

To provide a judgment perspective on how far one should go, Fig. 1 illustrates parametrically how the allowable turbine cost multiplier behaves as the turbine efficiency is improved. The ultimate η is unity of course, but this representation is insensitive to such conservation. Besides, one can derive by second-order turbine theory, an efficiency limit value of about .92. Beyond that, an idealized turbine becomes "power-less" as well as "friction-less". In reality, it becomes very difficult to "push" a design much beyond a value of about .80, regardless of \$, because of many practical limitations in materials and shaping.

There may be disguised in all this, an implication that, beyond a certain point, it becomes less profitable to further improve the turbine - but that's another exercise.

LFW:dmb

Figure 1 Turbine-TD Cost Multiplier

- r : Ratio of design efficiency to reference efficiency
- R : Ratio of design cost to reference cost
- p_0 : Ratio of collector cost to reference turbine cost

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