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The Cost and Value of Washing Heliostats

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THE COST AND VALUE OF WASHING HELIOSTATS

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ABSTRACT

An equation is derived for the washing frequency that minimizes cost per unit energy for solar collectors of any type. Central receiver heliostats of two designs are used in an example, and the results for Albuquerque soiling rates show that washing 15-30 times per year is worthwhile. The optimal frequency depends on the square root of such factors as the cost per wash and the daily loss in reflectivity, but it is not sensitive to number of collectors or plant size. The frequency for minimum cost per unit energy corresponds to the strategy of washing whenever the value of the extra energy from cleaner mirrors will pay for the cost of the wash.

1. INTRODUCTION

Solar collectors of all types collect dirt as well as sunlight. The dirt reduces the output of the collector, and the value of the resulting lost energy is the potential value of washing. The value of washing may substantially exceed the cost of washing, was the following example shows.

Face-up heliostats at China Lake, California, lost 25-35 percent of their clean reflectivities in six months due to soiling [1-3]. The loss in collected energy for a central receiver plant is roughly proportional to the loss of reflectivity, and lost energy is worth at least the current electricity price of $0.04/kWh. At that price, a drop in output of 30 percent represents lost energy worth about 5 M$ per year for a 100 MW plant. By comparison, washing 26 times per year would cost only 0.7 M$ and would recover 93 percent of the lost energy for a net savings of about 4 M$ per year.

This paper examines the tradeoff between the cost of washing and the value of the additional energy obtained. The primary contribution is an equation for the washing frequency that minimizes cost per unit energy. Central receiver heliostats provide a convenient example, but the equation applies to <u>any</u> solar collector which satisfies the analysis assumptions.

2. ANALYSIS

The analysis rests on three assumptions:

1. Loss in reflectivity per day, ℓ_r, is constant.
2. Washing restores reflectivity to a clean value, R_c.
3. The annual energy collected is proportional to average reflectivity, R, i.e., $E = KR$.

These assumptions are supported by available data [4], but the model is sufficiently robust that they could be relaxed. Assumptions 1 and 2 result in the following model for average reflectivity,

$$R = R_c - 365\ \ell_r/2f \qquad (1)$$

where f is the number of washes per year. The cost per unit energy, B, is the ratio of total annual plant cost to net annual energy production,

$$B = \left(\frac{1}{K}\right) \frac{C + 0 + NWf}{R_c - 182.5\ell_r/f} \tag{2}$$

where C is the annual capital charge, 0 is the non-washing operations and maintenance cost, and washing cost is the product of N = number of collectors, W = cost/wash/collector, and f. If average washing frequency over the life of the plant is desired, all annual costs should be levelized over the life of the plant, including the effects of taxation, depreciation, cost of money, and inflation. If R_c and ℓ_r vary over the life of the plant, a "levelized" or average value should be used to get the average washing frequency. The model can also be used with current costs to plan the current year's washing schedule.

The washing frequency that minimizes cost per unit energy is found by setting dB/df = 0 and solving the resulting quadratic equation for optimal frequency f_o. The result is

$$f_o = a + [a^2 + a(C + 0)/NW]^{1/2} \tag{3}$$

where

$$a = 182.5\ell_r/R_c.$$

3. EXAMPLE

Compare the optimum washing frequency and resulting energy cost for two 300 MW central receiver electric plants. One plant uses stowing glass heliostats with R_c = 0.92 and the other uses plastic dome heliostats with R_c = 0.65. The glass heliostats collect dust rapidly when operating but slowly when stowed vertically or inverted, and they are in the latter position about half the time. The plastic domes are assumed to collect dust all the time at the same rate as the operating glass heliostats.

3.1 Parameter Values. Estimates of the degradation rate vary widely [1-5]. Freese [4] presents plots of specular reflectance vs. days of exposure with regular washing at 2, 6, and 12 day intervals. These data are combined with (1) to estimate the average value ℓ_r = 0.005/day for continuous exposure and 6-12 day washing intervals. The value used for daytime operation and nighttime stow is ℓ_r = 0.003/day, based on estimates in [3].

The cost per wash per heliostat, W, is based on an estimate by McDonnell Douglas for washing 18 000 glass heliostats in 80 hours (Table 17 in [3]). That estimate is W = $2.13/wash/heliostat when levelized over 30 years. Scaling rules are assumed to get W for plastic heliostats, as follows:

1. Capital cost per heliostat for the washing equipment is identical.
2. Labor and fuel scale as the ratio: (dome circumference plus azimuthal spacing)/(glass width plus azimuthal spacing) = 2.6:1.
3. Water and soap scale as the ratio: (area of the upper 85 percent of the dome)/(glass area) = 4.8:1.

Rule 1 presumes a higher cost for the dome washing equipment, divided by a larger number of heliostats in the field (N = 63116 for plastic, N = 40281 for glass). More equipment is needed as f increases, but this effect is neglected since capital cost accounts for only 7 percent of W.

Rule 2 presumes that labor and fuel scale as the time spent, and that a vertical spray head moves past the surface and between heliostats at constant velocity for both domes and glass designs. Labor cost may increase as f increases because of shift differentials and larger crews, but it may also increase as f decreases if the crews are paid for idle time. Labor cost accounts for less than half of W. Rule 3 presumes that the same amount of water and soap per unit area is required to wash glass and plastic. Application of these rules to the levelized McDonnell Douglas estimate gives a scaled, levelized estimate of W = \$7.67/wash/heliostat for plastic domes.

The only remaining parameter in (3) is C + O, the annual cost of the plant with no washing. The default cost estimates and economic scenario in the code DELSOL [6] were used to estimate C + O = 82.18 M\$ per year for glass and 83.40 M\$ per year for plastic. These estimates are based on a sodium receiver with optimized tower height, receiver size, number of heliostats, and field layout for a 300 MW plant with each type of heliostat. The costs of the heliostats are \$65/m^2 and \$26/m^2 for glass and plastic, respectively.

3.2 <u>Results</u>. For the parameter values discussed above, the results from (3) and (1) are:

	Glass Heliostat	Plastic Heliostat
optimal f_0, washes per year	24.5	17.0
average reflectivity, R	0.90	0.60

To calculate the resulting cost per unit energy from (2), it is necessary to evaluate the constant $K = E_n/R_n$, where E_n is the nominal annual energy calculated by DELSOL for the optimized 300 MW plant with nominal reflectivity R_n. For the plants in this example, $K = 1.34 \times 10^9$ kWh for glass heliostats and $K = 1.95 \times 10^9$ kWh for plastic heliostats. Figure 1 gives the resulting plot of energy cost vs. washing frequency from (2). The

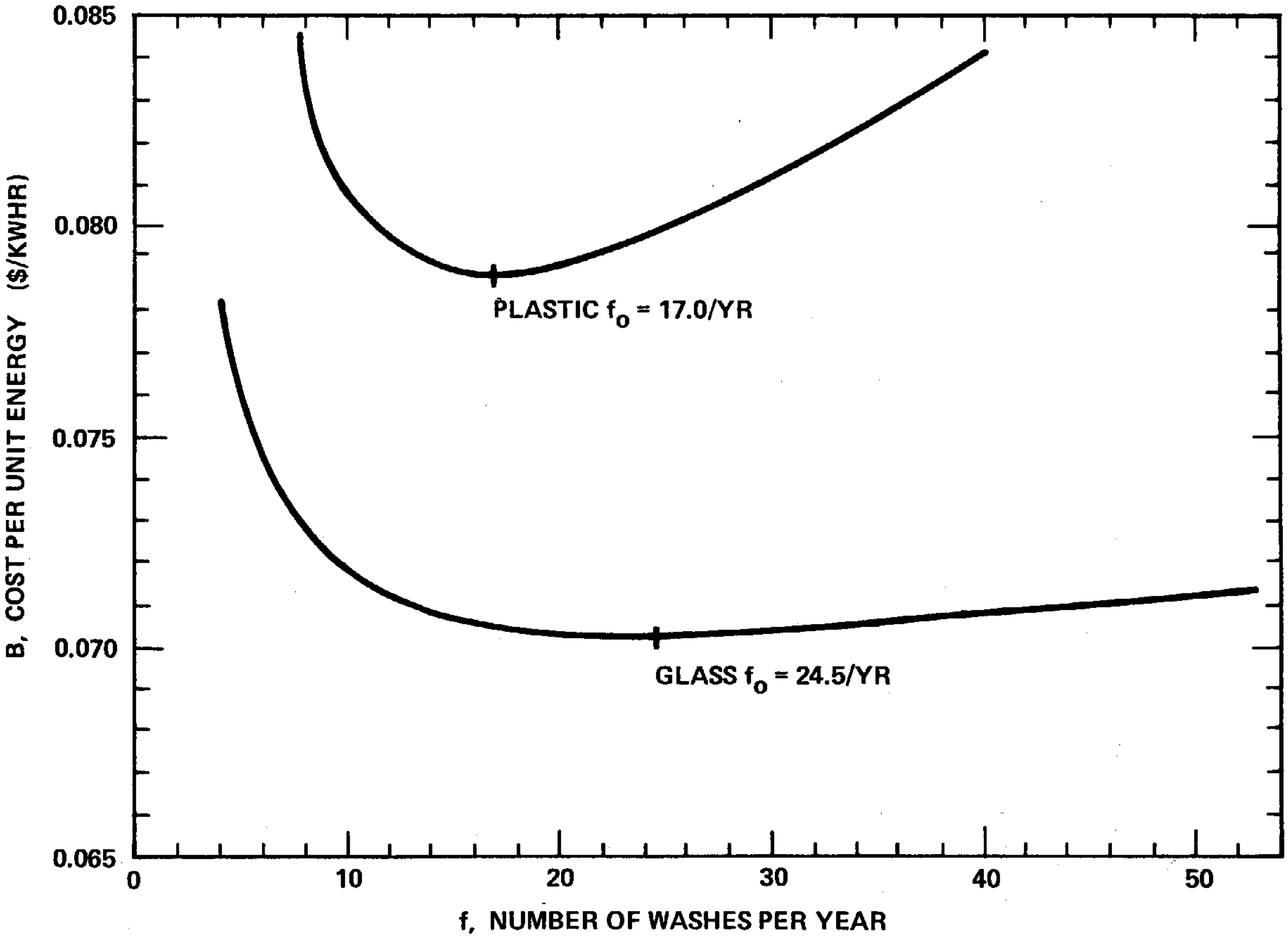

Figure 1. Energy cost vs. washing frequency for 300 MW electric plants using two heliostat designs.

minimum costs corresponding to the optimal frequencies are \$0.070/kWh and \$0.079/kWh for glass and plastic designs, respectively.

4. DISCUSSION

4.1 Limitations. The reflectivity model (1) suffers from two limitations. First, the degradation rate, ℓ_r, varies with weather and other factors; in particular frequent washing increases the average degradation rate as shown by estimates from data in [4].

for	f = 182.5/year	60.8/year	30.4/year
estimated	ℓ_r = 0.008/day	0.0054/day	0.0047/day

More data are needed for $f < 30$/year. Second, the effect of natural cleaning, primarily from rain, snow, and frost is not considered. Weather is sometimes very effective in restoring clean reflectivity values[1-5], and this is the major reason why unwashed reflectivities do not drop to zero as predicted by (1) for $f = 1$. Typical unwashed face-up reflectivities at Albuquerque are $0.84R_c$ after 200 days [4, p. 24] and $0.89R_c$ over one year [5], but at China Lake, CA, $0.75R_c$ and $0.65R_c$ were observed after six months [1,2]. Weather effects probably do not affect the optimal washing frequency for $f > 12$/year in regions with infrequent precipitation.

4.2 Alternate Forms of (3). The dominant term in (3) is

$$f_o = [182.5\ell_r\ (C + O)/NWR_c]^{1/2} \qquad (4)$$

For the Example, (4) gives values of f_o that differ from (3) by less than 10 percent. It is evident that factor of two changes in the parameters in (4) affect f_o by at most 40 percent.

If the plant cost C + O is unknown, (3) or (4) can be rewritten without that term. The cost per unit energy from the solar plant is approximately (C + O)/E, and if the solar plant competes with alternate energy sources with cost per unit energy B', then $B' \cong (C + O)/E$. DELSOL runs show that $E = K_1 N$ to within 1 percent for optimized plants in the range 100-300 MW. A typical value is K_1 = 29 710 kWh/heliostat for glass heliostats at R = 0.89. Then

$$(C + O)/N \cong B'E/N \cong B'K_1 \qquad (5)$$

which can be substituted into either (3) or (4). With (5) is is not necessary to know plant costs or even the size of the plant--the optimal washing frequency depends only on the value of competing energy B' ($/kWh) and the annual energy production per heliostat, K_1 (kWh).

4.3 A Practical Washing Strategy. A useful interpretation of the optimal frequency is obtained by introducing (5) into (4) and rearranging:

$$W = 182.5\ell_r B'K_1/R_c f^2 \qquad (6)$$

The right side of (6) is $-d(182.5\ _r B'K_1/R_c f)/df$, where $B'K_1$ is the value of the annual energy generated by one heliostat and $182.5\ell_r/R_c f = (R_c - R)/R_c$ is that fraction of the potential annual energy that is lost due to average dirtiness. So the right side of (6) can be interpreted as the change in the value of annual energy loss per heliostat for a unit change in f. W is similarly the change in the cost of annual washing per heliostat for a unit change in f. Simply stated, the optimum frequency from (3) or (4) corresponds to the practical strategy of washing as often as the increased washing cost is paid for by the increased energy value.

4.4 Can You Avoid Washing? Is it cost effective to add more heliostats and not wash? With current estimates of the parameters, the answer is no, because the optimum washing strategy is not sensitive to the number of heliostats in the field. This can be seen by increasing N by 18 percent in the Example. This increases the annual cost C + O by 6 percent, and f_0 from (3) decreases 5 percent, or about one wash per year. Since this is the optimal frequency, fewer or no washes per year will lead to higher costs per unit energy and so should not be considered. This is not the complete answer, however, because the average reflectivity model (1) breaks down as $f \to 0$, as discussed above.

Another partial answer is that it may be cost effective not to wash some heliostat designs in some locations. If the value of (C + O)/KR with no washing is less than B from (2) evaluated at f_0, then washing is not justified. This occurs for the Example if $R \geq 0.87 = 0.95R_c$ for glass heliostats or $R \geq 0.54 = 0.84R_c$ for plastic heliostats. The available data [1-5] suggest that natural cleaning will not maintain $R > 0.95R_c$, but there may be some locations where it will maintain $R > 0.84R_c$. Consequently, glass heliostats will always need some washing, but plastic heliostats may not in some locations. However, note that unwashed plastic heliostats do not compete with optimally washed glass heliostats unless natural cleaning maintains $R > 0.94R_c$, based on the data in the Example.

The complete answer must rely on a more complete washing model that considers the timing and frequency of both natural cleaning and washing. It is likely that it will be worthwhile to wash sometimes even with substantial natural cleaning, because the value of the extra energy collected by cleaner mirrors before the next expected rain will more than pay for the cost of the wash. The key principle is to wash whenever the value of the energy gained will pay for the wash; (3) and (4) merely give upper bounds on that frequency for negligible natural cleaning.

5. CONCLUSIONS

This investigation shows that washing heliostats is worthwhile, perhaps as often as 15-30 times per year depending on the cost of washing the heliostat, the local weather conditions, and other factors. The optimal frequency is not sensitive to plant size or the number of heliostats in the field at any particular plant size. The frequency that minimizes cost per unit energy also corresponds to the practical strategy of washing whenever the value of energy gained will pay for the wash.

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