SANDIA REPORT
SAND2013-8327
Unlimited Release
Printed September 2013

Levelized Cost of Coating (LCOC) for Selective Absorber Materials

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Abstract

A new metric has been developed to evaluate and compare selective absorber coatings for concentrating solar power applications. Previous metrics have typically considered the performance of the selective coating (i.e., solar absorptance and thermal emittance), but cost and durability were not considered. This report describes the development of the levelized cost of coating (LCOC), which is similar to the levelized cost of energy (LCOE) commonly used to evaluate alternative energy technologies. The LCOC is defined as the ratio of the annualized cost of the coating (and associated costs such as labor and number of heliostats required) to the average annual thermal energy produced by the receiver. The baseline LCOC using Pyromark 2500 paint was found to be \$0.055/MWh_t, and the distribution of LCOC values relative to this baseline were determined in a probabilistic analysis to range from -\$1.6/MWh_t to \$7.3/MWh_t, accounting for the cost of additional (or fewer) heliostats required to yield the same baseline average annual thermal energy produced by the receiver. A stepwise multiple rank regression analysis showed that the initial solar absorptance was the most significant parameter impacting the LCOC, followed by thermal emittance, degradation rate, reapplication interval, and downtime during reapplication.

CONTENTS

1. Introduction **5**

2. Approach **6**
2.1. Selective Absorber Efficiency 6
2.2. Definition of the LCOC 7

3. Application and Results **7**
3.1. Baseline LCOC for Pyromark 2500 7
3.2. Probabilistic Evaluation of LCOC for Alternative Materials 10

4. Conclusions **15**

References **17**

Distribution **18**

FIGURES

Figure 1. Sandia's Concentrating Solar Power Tower at the National Solar Thermal Test Facility, Sandia National Laboratories, Albuquerque, NM. 5
Figure 2. Pyromark paint was used on the central receivers at Solar One [1] and Solar Two [2] (shown above). 6
Figure 3. Annualized costs per MWh_{th} of absorbed energy for Pyromark 2500. The total LCOC is $0.055/$MWh_{th}$. 10
Figure 4. Cumulative distribution function of the LCOC with 1000 realizations. 12
Figure 5. Standardized rank regression coefficient of the various input parameters showing the relative importance of each parameter on the calculated LCOC value. The sign of the coefficient indicates a positive or negative correlation. 13
Figure 6. Incremental coefficient of determination showing the importance of the uncertainty of various input parameters on the spread of the calculated LCOC distribution. 14

TABLES

Table 1. Parameters used in baseline LCOC calculation with Pyromark 2500. 8
Table 2. Pyromark 2500 performance and cost parameters. 9
Table 3. Input parameter uncertainty distributions for probabilistic LCOC analysis of alternative selective absorber materials. 11
Table 4. Probabilistic LCOC comparisons. 15

1. INTRODUCTION

Concentrating solar power (CSP) is a renewable energy technology that converts solar thermal energy to electricity via a heat engine and generator. These systems are typically large—capable of generating tens to hundreds of megawatts of electricity. Over 500 MW of concentrating solar power have been installed in the United States as of 2012, with over 700 MW of additional CSP plants currently under construction.

Concentrating solar power systems use large arrays of mirrors to reflect and concentrate the sunlight onto receivers that heat a working fluid. Several mirror configurations are possible, including dishes, parabolic troughs, linear Fresnel, and heliostats. One of the most promising CSP technologies is the central receiver (or power tower) system, which consist of a field of large, nearly-flat mirror assemblies (heliostats) that track the sun and focus the sunlight onto a receiver on top of a tower [1, 2] (Figure 1). In a typical configuration, a heat-transfer fluid such as water/steam or molten salt is heated in the receiver and used to power a conventional steam-turbine Rankine cycle to generate electricity. Excess thermal energy collected in molten salts can be stored in large insulated tanks allowing operation of the steam turbine during the night or on cloudy days.

Figure 1. Sandia's Concentrating Solar Power Tower at the National Solar Thermal Test Facility, Sandia National Laboratories, Albuquerque, NM.

The efficiency of a power tower can be increased if the energy absorbed by the receiver is maximized while the heat loss from the receiver to the environment is minimized. As materials get hot, energy is radiated away in the infrared wavelengths. Thus, heat loss occurs because of thermal radiation losses from the hot receiver surface to the environment as well as from convection due to wind and buoyancy effects.

Increased central receiver operating temperatures (>600°C) are needed to increase power cycle efficiency, reduce material costs for thermal storage, and lower the overall cost of electricity from CSP. However, higher operating temperatures result in increased energy loss due to thermal radiation. Therefore, research is being conducted to identify selective absorber coatings that will maximize solar absorptance in the visible and near-infrared wavelengths (~400 – 2500 nm) while minimizing thermal emittance in the infrared wavelengths (~1 – 20 microns) [3-5]. Because these spectra overlap, especially at higher temperatures, development of selective coatings is challenging. Additionally, these selective absorber coatings should be durable at high temperatures in exposed environments to avoid degradation.

Pyromark® Series 2500 high temperature paint has been used on previous CSP central receivers (Figure 2) and is considered a standard [1, 2, 6]. Pyromark 2500 is relatively inexpensive, easy to apply, and has a measured solar absorptance of 0.96 (new) [6]. However, with a thermal emittance of 0.87 it suffers from large thermal losses during high temperature operation. It also showed significant degradation at higher temperatures (>700°C) when operated in air, causing a decline in performance and potentially added operating costs for CSP facilities [6].

Figure 2. Pyromark paint was used on the central receivers at Solar One [1] and Solar Two [2] (shown above).

The objective of this report is to introduce a new metric, called the Levelized Cost of Coating (LCOC), that can be used to evaluate and compare alternative materials against Pyromark 2500. The LCOC accounts for both annualized cost and performance of the coating.

2. APPROACH

2.1. Selective Absorber Efficiency

A significant amount of effort and studies have focused on the development of high-temperature solar selective coatings with high solar absorptance and low thermal emittance [3-7]. Typically, the metric used for selective absorber coatings is based on the net absorptance of energy relative to that of an ideal absorber. Cindrella [7] and Ho et al. [6] presented the following definition for the efficiency of selective absorbers, η_{sel}, which is equal to the ratio of the net radiative energy absorbed and retained by a surface to the net radiative energy absorbed and retained by an ideal selective absorber with an absorptance of one and an emittance of zero:

$$\eta_{sel} = \frac{\alpha_s Q - \varepsilon \sigma T^4}{Q} \tag{1}$$

where α_s is the solar absorptance, Q is the irradiance on the receiver (W/m^2), ε is the thermal emittance, σ is the Stefan-Boltzmann constant (5.67x10^{-8} W/m^2/K^4), and T is the surface

temperature (K). In this study, we assume the irradiance, Q, is 600 kW/m^2 (600 suns), and T is 700 °C.[1] Currently deployed power tower systems typically operate at a lower irradiance (<500 suns) and temperature (<600 °C). This metric is useful for comparing the performance of different selective absorber coatings, but it does not account for other important factors such as cost and durability.

2.2. Definition of the LCOC

In this work, we introduce a new metric, similar to the levelized cost of electricity (LCOE), that accounts for annualized performance, costs, and reliability/durability. This new metric, called the levelized cost of coating (LCOC), is defined as the ratio of the total annualized coating costs ($) to the annual thermal energy absorbed (MWh_{th}):

$$\text{LCOC (Levelized Cost of Coating)} = C_{annual}/E_{thermal} \quad (2)$$

where

C_{annual} = total annualized coating costs

= initial coating cost/life of plant + recoating costs/recoating interval + cost of additional (or fewer) heliostats to yield a baseline thermal energy production

$E_{thermal}$ = average annual energy absorbed

= annual thermal energy absorbed (new) – annualized lost energy absorbed due to degradation – annualized lost energy absorbed due to down time for re-coating

These parameters depend not only on the selective absorber efficiency, η_{sel}, which impacts the thermal energy absorbed, but also on degradation rate, downtime, material costs, and reapplication costs. The LCOC metric provides a more comprehensive means of comparing alternative coatings and selective absorbers for use in concentrating solar power systems.

3. APPLICATION AND RESULTS

3.1. Baseline LCOC for Pyromark 2500

A baseline LCOC for Pyromark 2500 was determined that accounts for not only performance (selective absorber efficiency) but also costs associated with materials, initial application, reapplication, and lost revenue from downtime and degradation. We assumed a 100 MW_e molten-salt power plant with a ~50% capacity factor to define the receiver size and heliostat field area (Table 1). The annual thermal energy absorbed was assumed to be affected by the collector efficiency, receiver efficiency (which includes the selective absorber efficiency), and parasitic losses. The degradation rates and costs associated with materials, application, reapplication,

[1] With these values, Eq. (1) shows that the relative weighting (importance) of the solar absorptance is over 10 times greater than the weighting of the thermal emittance.

downtime, and degradation are based on available data from Solar One [1], Ho et al. [6], and consultation with engineers from Babcock & Wilcox (Table 2).

Table 1. Parameters used in baseline LCOC calculation with Pyromark 2500.

Parameter	Value	Comments
Power capacity (MW_e)	100	
Plant life (years)	30	
Capacity factor	0.5	
Receiver thermal rating (MW_t)	540	
Receiver area (m^2)	1005	Based on 16 m diameter x 20 m tall receiver
Number of receiver panels	16	Arranged in a cylinder for surround field
Heliostat field area (m^2)	1.17×10^6	
Annual Direct Normal Irradiance (DNI) ($kWh/m^2/y$)	2700	Based on location in southern California
Selective absorber efficiency	0.89	Using Eq. (1) using Pyromark parameters (see Table 2) assuming Q=600 kW/m^2 and T=700°C
Thermal collection efficiency (excluding selective absorber efficiency)	0.44	This accounts for cosine losses, availability, heliostat defocus, mirror reflectivity, cosine losses, blocking & shading, atmospheric attenuation, spillage, startup losses, convection, conduction, and receiver piping losses. It does not include absorptance and thermal emittance losses, which is accounted for in the selective absorber efficiency.
Annual solar-to-thermal total collection efficiency	0.39	Product of selective absorber efficiency and thermal collection efficiency

Table 2. Pyromark 2500 performance and cost parameters.

Parameter	Value	Comments
Solar absorptance	0.96	[6]
Thermal emittance	0.87	[6]
Selective absorber efficiency	0.89	Using Eq. (1) assuming Q=600 kW/m^2 and T=700°C
Degradation rate (%/year)	0.5	Assumes linear degradation of energy absorbed during the period between reapplications
Reapplication interval (years)	5	Based on Solar One data [1]
Downtime during reapplication (days)	12	Based on Solar One data [1]
Material cost ($/m^2)	5.41	Based on current Pyromark 2500 paint cost ($200/gallon) and coverage (37 m^2/gallon) [6]
Initial application cost ($/m^2)	287	Includes costs associated with furnace oven to cure paint initially, instrumentation, IR camera, and labor to prepare, paint, and cure surface and conduct measurements and quality assurance
Reapplication cost ($/m^2)	286	Includes paint cost, rigging and SkyClimber for repainting, and labor for surface preparation, painting, on-sun curing, property measurements, and quality assurance.

The estimated LCOC for Pyromark 2500 using Eq. (2) and the values in Table 1 and Table 2 was calculated to be \$0.055/MWh$_{th}$. The cost contributions to the LCOC are shown in Figure 3. Results show that the major LCOC costs for Pyromark 2500 are the reapplication costs. The initial material and labor costs were relatively small in comparison. The average annual thermal energy absorbed (accounting for absorber efficiency, degradation, and downtime) was 1.2x10^6 MWh$_t$/y. The annual thermal energy production when the paint was new was 1.24x10^6 MWh$_t$/y, but the lost annual thermal energy due to downtime and coating degradation was 8,140 MWh$_t$/y and 1.55x10^4 MWh$_t$/y, respectively.

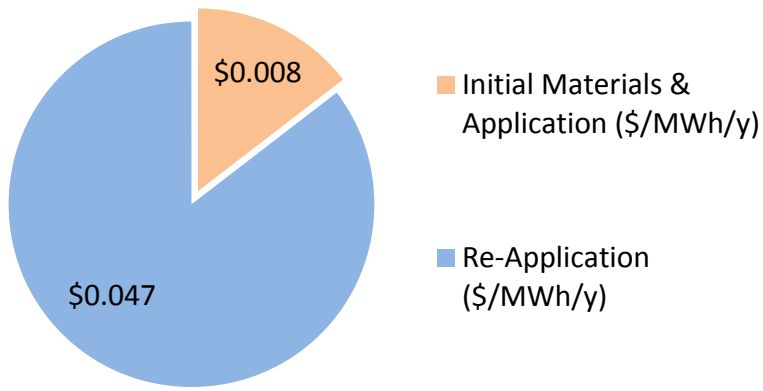

Figure 3. Annualized costs per MWh_{th} of absorbed energy for Pyromark 2500. The total LCOC is $0.055/$MWh_{th}$.

It is important to note that while the above calculation provides an LCOC value for a baseline thermal energy production from the receiver using Pyromark 2500, a more important value for comparison is the relative value of the LCOC for other coatings, which will depend on the costs of more (or fewer) heliostats to achieve the same average annual thermal energy production as the baseline case with Pyromark 2500. If the performance of a selective absorber is superior to Pyromark 2500 and more annual thermal energy is produced by the receiver, then fewer heliostats will be required, and costs will decrease. Alternatively, if the performance of a selective absorber is worse than Pyromark 2500, more heliostats will be required to maintain the same baseline annual average thermal energy production, and costs will increase.

The annualized costs associated with more or fewer heliostats ($/$MWh_t$/y) is calculated as the difference in average annual thermal energy produced (relative to Pyromark 2500), converted from MWh to Wh, divided by the number of operational hours per year assuming a 0.5 capacity factor to yield the relative thermal power produced by the receiver (W), divided by the DNI (1000 W/m^2) and the annual collection efficiency of the heliostat field (assumed to be 0.6) to get the extra (or reduced) mirror area required (m^2), multiplied by the heliostat cost per m^2 (assumed to be $75/$m^2$ per SunShot target), divided by the average annual thermal energy production for the Pyromark 2500 baseline case (MWh_t/y) to yield the cost per MWh_t per year. If the assumed DNI is less and/or the assumed heliostat cost is greater than the values assumed here, the relative LCOC values will be more extreme than those reported here.

3.2. Probabilistic Evaluation of LCOC for Alternative Materials

To better understand the uncertainty of the LCOC and its sensitivity to various input parameters for Pyromark 2500 and other candidate materials being developed, a probabilistic analysis was performed. Table 3 shows the input parameter uncertainty distributions used in the analysis. The nominal values were based on Pyromark 2500 and available data from Solar One [1], Ho et al. [6], and information from other power tower applications. The uncertainty distributions about the nominal values were assumed to be uniform with minimum and maximum values based on available data (e.g., radiative properties of candidate materials being developed for this project) and professional judgment. Note that the plant life was assumed to be fixed at 30 years.

Table 3. Input parameter uncertainty distributions for probabilistic LCOC analysis of alternative selective absorber materials.

Input Parameter	Baseline (Pyromark 2500)	Min	Max
Initial Absorptance	0.96	0.75	0.97
Initial Emittance	0.87	0.4	0.9
Coating material cost ($/m^2)	$5.41	$5.00	$50.00
Initial coating application cost ($/m^2)	$287	$143	$430
Plant life (years)	30	30	30
Re-application interval (years)	5	1	15
Reapplication cost ($/m^2)	$286	$142.85	$428.56
Downtime during reapplication (days)	12	6	18
Degradation rate (%/year)	0.50%	0.25%	0.75%

One-thousand realizations were randomly sampled from the distributions in Table 3, and Eq. (2) was used to solve for the LCOC. Figure 4 shows a plot of the cumulative distribution function of the LCOC values relative to the baseline LCOC with Pyromark 2500. Calculated values range from -$1.6/MWh$_t$ to $7.3/MWh$_t$. Thus, while the baseline LCOC value for Pyromark 2500 is quite low (in the 10th percentile of the cumulative distribution), there is opportunity for nearly $2/MWh$_t$ (~0.4 cents/kWh$_e$ LCOE) of cost reduction using the assumed values in this study.

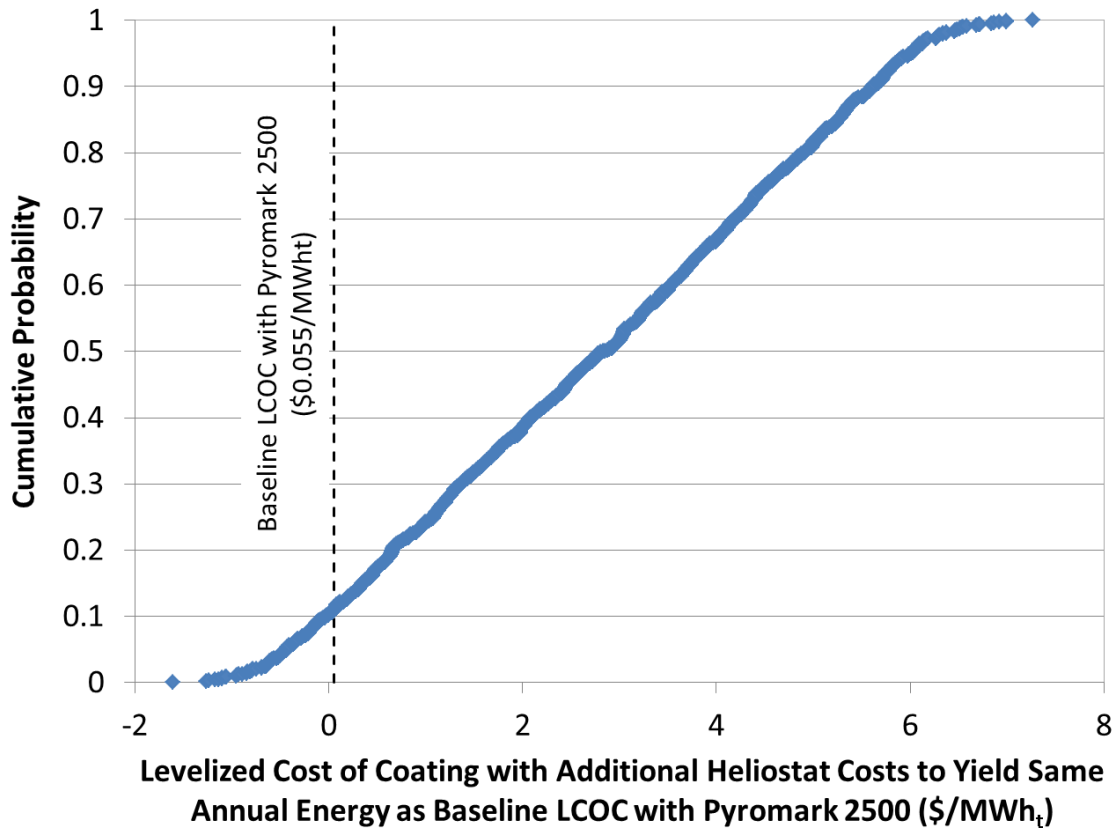

Figure 4. Cumulative distribution function of the LCOC with 1000 realizations.

Figure 5 shows the standardized rank regression coefficients (β) from a multiple regression analysis to determine the relative importance of the input parameters on the calculated value of the LCOC. The sign of the β coefficients indicates a positive or negative correlation with the LCOC. For example, the β coefficient for the initial absorptance was -0.98, which indicates a strong negative correlation with the LCOC. As the solar absorptance increased, the LCOC decreased. The initial absorptance was found to be the most significant parameter, followed by the thermal emittance, degradation rate, reapplication interval, and downtime during reapplication. The material and application costs were not found to be statistically significant to the LCOC calculation (using the assumed values in this study). As a result, the reapplication interval was positively correlated to the LCOC. In other words, a longer interval period between reapplication of the coating resulted in a higher LCOC. More frequent reapplications increased the solar absorptance, which increased the average annual thermal energy production from the receiver and reduced the number of heliostats and costs required to produce the same baseline thermal energy required. It should be noted that the reapplication interval was sampled independently from the degradation rate. An interesting follow-on study would be to use the LCOC model to determine the optimal reapplication interval for a prescribed selective absorber material that minimizes the LCOC. Deterministic values (or probabilistic uncertainty distributions) can be applied to the required input parameters in the model, and the LCOC can be

calculated for different values of the reapplication interval. This reapplication interval would serve as a practical guide for plant operations at new and existing sites.

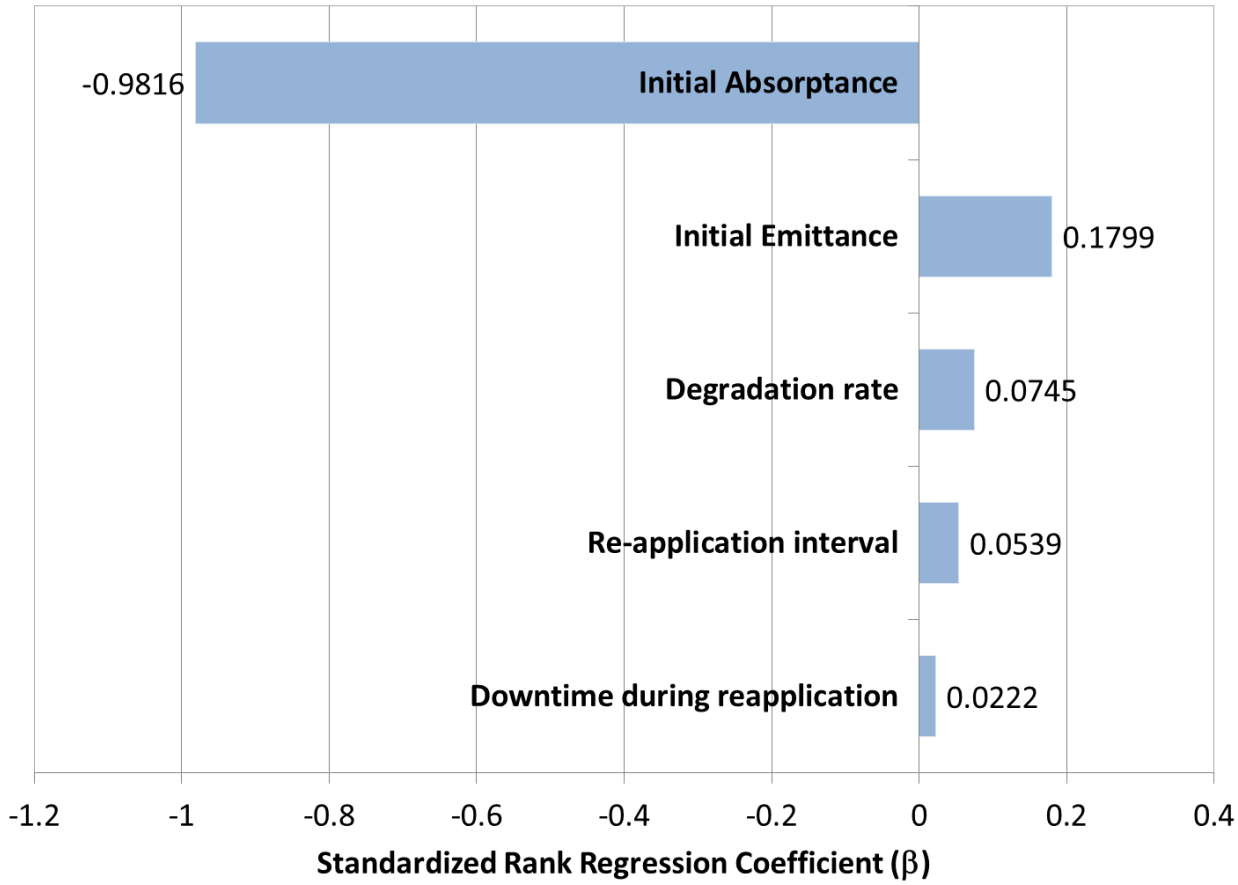

Figure 5. Standardized rank regression coefficient of the various input parameters showing the relative importance of each parameter on the calculated LCOC value. The sign of the coefficient indicates a positive or negative correlation.

A stepwise rank regression analysis was also performed to determine the importance of the input parameters on the uncertainty in the LCOC distribution. Figure 6 shows a graph of the incremental coefficients of determination (ΔR^2), which indicate the importance of the uncertainty of various input parameters on the spread of the calculated LCOC distribution. For example, the ΔR^2 for the initial absorptance is 95%, which means that nearly 95% of the variability in the LCOC distribution can be explained by the uncertainty in the initial absorptance. Combined with the ΔR^2 of the initial emittance (3.3%), the uncertainty in both the initial absorptance and emittance parameters can explain ~98% of the variability in the calculated LCOC.

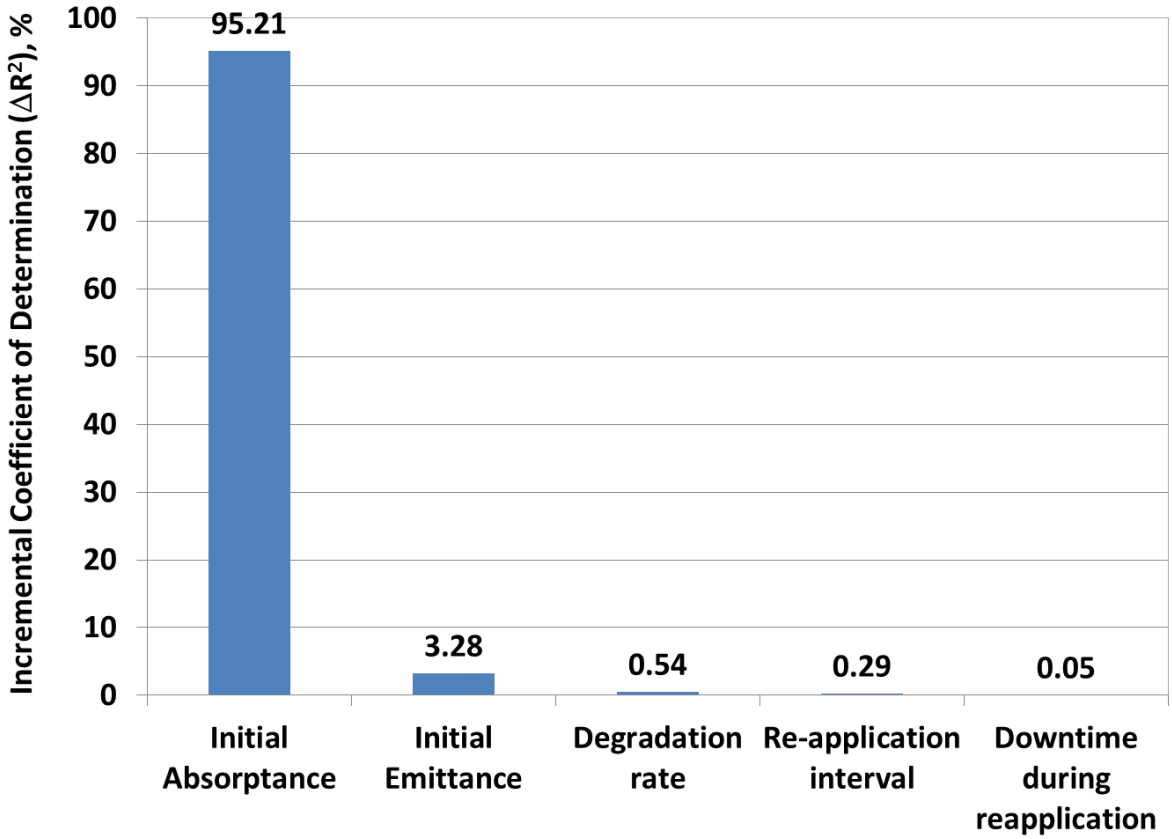

Figure 6. Incremental coefficient of determination showing the importance of the uncertainty of various input parameters on the spread of the calculated LCOC distribution.

Table 4 shows representative values of the key input parameters for the calculated baseline, minimum, and maximum LCOC values out of the 1000 realizations that were sampled. The realization with the lowest LCOC sampled a relatively large initial absorptance, low thermal emittance, average degradation rate, low reapplication interval, and low downtime. The realization with the highest LCOC sampled a relatively low initial absorptance, high thermal emittance, high degradation rate, high reapplication interval, and average downtime. These relative values correspond to the correlations and results of the multiple regression analyses shown in Figure 5 and Figure 6.

Table 4. Probabilistic LCOC comparisons.

	Initial Absorptance	Initial Emittance	Degradation rate (%/year)	Re-application interval (years)	Downtime during reapplication (days)	LCOC ($/MWh$_t$)
Pyromark 2500 Baseline LCOC	0.96	0.87	0.50%**	5.0	12.0	$0.055
Lowest LCOC*	0.97	0.41	0.47%	2.2	7.2	-$1.61
Highest LCOC*	0.76	0.90	0.59%	14.6	12.8	$7.27

*Considers costs associated with additional (or fewer) heliostats required to yield same annual energy production as Pyromark 2500 baseline (additional costs associated with changes in receiver size are not considered)
**Significantly greater degradation rates have been shown to occur at temperatures ~750 C and higher [6]

4. CONCLUSIONS

A new system-level metric, the LCOC (Levelized Cost of Coating) has been developed to provide a more comprehensive comparison among solar selective coatings. Initial and recurring costs have been integrated in the new LCOC metric, along with performance metrics (e.g., selective absorber efficiency). Nominal values for Pyromark 2500 have been estimated using available data, and ranges of potential LCOC values for candidate selective absorber coatings have been provided using uncertainty distributions and probabilistic analyses.

The annualized LCOC for Pyromark 2500 was found to be $0.055/MW$_{th}$. The average annual thermal energy production using Pyromark 2500 ($1.2x10^6$ MWh$_t$) was used as a baseline, and additional probabilistic studies were performed to evaluate the LCOC range for other candidate materials and ranges of parameters. The cumulative distribution function for 1000 realizations showed that the LCOC could range from -$1.6/MWh$_t$ to $7.3/MWh$_t$ relative to the Pyromark 2500 baseline. A stepwise rank regression showed that the initial solar absorptance was the most significant parameter impacting the LCOC, followed by thermal emittance, degradation rate, reapplication interval, and downtime during reapplication. A low solar absorptance or large thermal emittance reduced the amount of thermal energy produced by the receiver, requiring additional heliostats (and costs) to recoup the lost energy relative to the baseline using Pyromark 2500. In contrast, realizations with high solar absorptance and low thermal emittance increased the thermal energy production of the receiver, reducing the number of heliostats (and costs) required to maintain the baseline average annual thermal energy produced by the receiver.

It should be noted that while a baseline degradation rate of 0.5%/year was used for Pyromark 2500 based on Solar One data [1], additional tests have shown that the degradation rate can be significantly higher at temperatures over 700 °C [6]. In addition, proper application and curing methods of Pyromark 2500 are required to maintain low degradation rates [6].

This study has shown that selective absorber coatings with high initial absorptance and low thermal emittance are important to reducing the LCOC. In addition, increasing the durability (reducing the degradation rate and downtime during reapplication) will reduce the LCOC. An interesting finding is that for the costs and values assumed in this study, reducing the reapplication interval also reduced the LCOC. This indicates that maintaining a high solar absorptance outweighed the costs associated with more frequent reapplications. If the costs associated with reapplication are significantly higher than the costs assumed here, these conclusions may change.

Finally, an interesting and practical use of the LCOC model would be to determine the optimal reapplication interval for a given selective absorber material. Uncertainty distributions (or deterministic values) could be assigned to the absorptance, emittance, degradation, downtime, and other parameter values for a particular material, and the model could be used to find the optimal reapplication interval that produced the minimal LCOC.

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