Durability of solar absorber coatings and their cost-effectiveness

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ABSTRACT

Solar absorber coatings are said to be “cost-effective” when significant efficiency gains are achieved with an acceptable additional cost. Here, an integrated approach to solar power technologies is used for quantifying more rigorously the cost-effectiveness of coatings in the concentrating solar power (CSP) industry. The levelized cost of electricity (LCOE) metric is used in an original way that attributes a cost-effectiveness value to any high-temperature absorber coating via a figure of merit named the LCOE gain efficiency. The LCOE gain efficiency is demonstrated on three different solar absorber coatings: Pyromark 2500, lanthanum strontium manganite oxide (LSM), and cobalt oxide (Co_3O_4), that coat a hypothetical 100 MW_e central tower receiver. To perform the calculation of the LCOE gain efficiency, accelerated aging tests and cost estimates are performed. Depending on the coating properties, an optimal reapplication interval may be found that minimizes the LCOE of the plant, i.e., maximizes the LCOE gain efficiency. In such optimal conditions—and for this typical power tower—Pyromark 2500 paint enables a higher LCOE gain efficiency (0.182) than both LSM (0.139) and Co_3O_4 (0.083). The solar absorptance is by far the most influential parameter. The cost-effectiveness of Pyromark could be outperformed by a coating that would have a high initial solar absorptance (> 0.95), a low initial degradation rate ($< 2 \times 10^{-6} \text{ cycle}^{-1}$), and a low cost ($< \500 k per application). Application of the LCOE gain efficiency can provide a consistent and objective method to evaluate a variety of receiver designs and other components.

1. Introduction

The current development of concentrated solar power (CSP) plants relies on higher conversion efficiencies, greater reliability and lower costs. High-temperature solar selective receivers that increase the solar radiation input, and reduce heat losses are desired. Much effort is currently invested in the development of high-temperature selective coatings that are efficient, durable and inexpensive. New materials must show better performance, not just on nominal or initial characteristics, but on efficiency, aging, cost, and global outcomes. The cost-effectiveness is demonstrated as an integrated metric of these characteristics.

The efficiency of a solar absorber describes its ability to absorb solar radiation and transfer heat to the heat fluid. It is captured by the thermal efficiency (TE) which is the ratio of the transferred power to the incident radiant flux. TE is an instantaneous value that is subject to cyclical variations at different timescales (day, month, year), depending on the internal and external thermodynamic conditions, e.g., solar flux, temperature, etc. For this reason, a single TE value calculated under arbitrary conditions may not be sufficient to describe the global

efficiency of an absorber. To address this, TE is often calculated under nominal conditions of temperature and solar irradiance then compared to that of other solar absorbers. But again, assuming a constant TE value is misleading because it overlooks the irreversible degradations due to aging phenomena. Consequences include an overestimated power output, underestimated costs, and overestimated lifetimes. For the above-mentioned reasons, aging must be taken into account.

Aging is generally defined in this paper as the alteration process of an entity's functionality resulting from out-of-equilibrium thermodynamic processes. A degraded functionality results in negative aging, otherwise the aging is neutral (no change) or positive when the functionality is improved. Solar absorbers may possess multiple functionalities and age in various ways [1]. However, their main function being to absorb and transfer the solar radiation, the evolution of TE is used to characterize their aging [2].

A third aspect of solar absorbers is cost. Cost is a major criterion to adopt one technology over the other. Absorber coatings are made of different materials and are often prepared with mature techniques such as spray-painting, thermal spray, or electrodeposition. Some coatings may require a pre-treatment (e.g. curing) so they achieve their highest

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efficiency – an example of positive aging. After a period of time in operation, the receiver coating might need to be “refreshed” by a new layer deposition or possibly reconditioned. Such actions are intended to restore the initial absorber efficiency, but obviously incur additional costs. These may become prohibitive if the material becomes less available or if the corresponding coating technique is difficult to apply on large scale. Preparation, operation, and maintenance costs must be estimated.

Ho et al. developed such a metric with the introduction of the Levelized Cost of Coating (LCOC) [3]. The model presented here was built upon the LCOC to develop a parameter based on the Levelized Cost of Energy (LCOE). It was shown to identify potential cost savings due to cost-effective components [4]. Two parameters were introduced: the “LCOE gain” due to the coating or $(\Delta LCOE)_c$, and the LCOE gain efficiency, or $\eta_{(\Delta LCOE)_c}$. The following study presents the application of the LCOE gain rationale to three different coatings: commercially available Pyromark 2500, and experimentally developed thermal-sprayed lanthanum strontium manganite oxide (LSM), and electro-deposited cobalt oxide (Co_3O_4).

First, the thermal efficiency of the three coatings is investigated with accelerated aging tests. Second, a cost estimation of each coating is performed in the case of a typical 100 MW power tower. Third, $(\Delta LCOE)_c$ and $\eta_{(\Delta LCOE)_c}$ are calculated and analyzed for each coating. A sensitivity study that was initiated in [4] is carried on in order to understand what parameters are the most impactful on the defined cost-effectiveness. Finally, the developed metrics are valuable indicators to the CSP industry for which cost-effectiveness and optimal maintenance scheduling are key issues.

2. The LCOE metric

Developing efficient renewable energies and achieving resource efficiency are major goals emphasized by several institutions [5–7]. All agree that current metrics are limited when it comes to comparing different technologies based on their efficiency, cost, and environmental impacts. They all mention the need for more life-cycle and systems oriented metrics. The LCOE is a well-known parameter whose usefulness and limitations were discussed previously [4]. It accounts for the total cost of a plant over the total electrical energy output. It is defined as the sum of the costs C_i of each component i , over the total amount of electrical energy produced, E_e :

$$LCOE = \frac{\sum_i C_i}{E_e} [\text{\$MW}^{-1} \text{h}^{-1}] \quad (1)$$

Component i can be any component, sub-component or group of sub-components as long as the sum is consistent. C_i includes the initial costs as well as the operation and maintenance costs of this component. It is convenient to annualize the costs and the energy production by dividing by the service lifetime of the plant.

$(\Delta LCOE)_c$ is the LCOE gain of a plant due to the application of a coating c , relative to a reference LCOE value with no coating (Eq. (2)):

$$(\Delta LCOE)_c = LCOE - LCOE_{ref} \quad (2)$$

$(\Delta LCOE)_c$ expresses a direct increase or decrease of the LCOE due to the use of coating c . The reference LCOE is chosen as the LCOE value of a non-coated receiver (i.e. bare metal). If $(\Delta LCOE)_c$ is negative, then $LCOE_c < LCOE_{ref}$ and the coating is considered “cost-effective”. If $(\Delta LCOE)_c$ is positive, $LCOE_c > LCOE_{ref}$, and the coating is declared “not cost-effective”.

Let $LCOE_{id}$ be the minimum possible value for the LCOE in a given plant configuration, achieved with an ideal coating id . Coating id is perfectly selective ($\alpha_s=1$, $\varepsilon_T=0$), perfectly durable (no degradation), and perfectly inexpensive (i.e., free). Then the maximum possible gain is:

$$(\Delta LCOE)_{id} = LCOE_{id} - LCOE_{ref} \quad (3)$$

Table 1

Entry data for the LCOE gain calculation. The highlighted section contains the variable parameters, which pertain to the coating used. The following “Section 3” explains how they are estimated for each coating.

Data	Comments
PLANT	
Annual solar energy density ($W h/m^2/year$)	At location of plant
Average sunlight hours per day (h/day)	At location of plant, operation hours
Nominal electrical power output (W)	Net capacity
Capacity factor (-)	
Service lifetime (year)	Example: 30 years
Total cost of plant (\\$)	Total costs excluding coating cost. Estimated based on an average LCOE of $\$230 \text{ MW}_e^{-1} \text{h}^{-1}$.
Annual solar-to-electricity efficiency	
Power block efficiency	
RECEIVER	
Receiver area (m)	Irradiated section area (actual area accounting for curvature of tubes)
Receiver temperature (K)	Characteristic surface temperature
Receiver availability	Accounting for downtime
Ambient temperature (K)	
Working fluid temperature (K)	Average
External convection coefficient ($W m^{-2} K^{-1}$)	Heat losses
“On-sun” service lifetime	Total time under concentrated solar flux
MATERIALS	
Solar absorptance of metal receiver	Assuming metal is oxidized
Thermal emittance of metal receiver	Assuming metal is oxidized
Evolution of coating thermal efficiency vs. on-sun time	Extrapolated evolution based on initial solar absorptance, initial degradation rate, end-of-life absorptance, constant emittance
Coating initial cost (\\$)	Total cost for initial coating
Coating reapplication cost (\\$)	Total cost for each reapplication
Reapplication interval RI (-)	Example: reapplication every 2 years
Downtime per reapplication DT (days)	Example: 10 days for recoating+treatments

$(\Delta LCOE)_{id}$ is always a negative number as $LCOE_{id} < LCOE_{ref}$. The “LCOE gain efficiency” $\eta_{(\Delta LCOE)_c}$ is defined as the ratio between $(\Delta LCOE)_c$ and $(\Delta LCOE)_{id}$:

$$\eta_{(\Delta LCOE)_c} = (\Delta LCOE)_c / (\Delta LCOE)_{id} \quad (4)$$

$\eta_{(\Delta LCOE)_c}$ ranges from $-\infty$ to 1. $\eta_{(\Delta LCOE)_c} \leq 0$ indicates a coating that is not cost-effective; $0 \leq \eta_{(\Delta LCOE)_c} \leq 1$ indicates a (more or less) cost-effective coating; $\eta_{(\Delta LCOE)_c} = 1$ indicates an ideal coating (perfectly selective, inexpensive, and durable).

The $(\Delta LCOE)_c$ numerical expression (equivalent to the previously introduced *absolute LCOC*) is discussed in more detail in [4]. Table 1 shows the model input parameters organized in three different sets of data: the power plant, receiver, and material data.

3. Method

The method section explains how Table 1 is populated.

3.1. Plant and receiver data

We consider a hypothetical 100 MW_e solar tower located close to Las Vegas, Nevada, USA. Table 2 presents the assumed metrics,

Table 2
Plant and receiver metrics.

PLANT	
Annual solar energy density (W h/m ² /year)	2500
Average sunlight hours per day (h/day)	6.4
Nominal electrical power output (W)	100
Capacity factor (-)	0.25
Service lifetime (year)	30
Total cost of plant (\$)	1.512×10 ⁹
Annual solar-to-electricity efficiency (-)	0.29
Power block efficiency (-)	0.625(1-T _{amb} /T _w)
RECEIVER	
Receiver area (m ²)	1005
Receiver temperature (K)	973
Receiver availability (-)	0.95
Ambient temperature (K)	293
Working fluid temperature (K)	680
External convection coefficient (W m ⁻² K ⁻¹)	20
“On-sun” service lifetime (years in operation)	8

inspired by the US commercial plants Ivanpah and Crescent Dunes. The cost of the plant is estimated via an average LCOE of current solar power plants: \$230 MW_e⁻¹ h⁻¹ in 2012 [8].

3.2. Evolution of the thermal efficiency

Actual aging data from CSP plants are scarce. Extended service lifetimes and the variety of operating conditions make each receiver unique. The same coating may not perform the same on all receivers. The thermal efficiency, η_{th} , is expressed as (Eq. (5)):

$$\eta_{th}(t_{os}) = \frac{\alpha_s(t_{os})\Phi_{i,nom} - \varepsilon\sigma T_{nom}^4 - hS(T_{nom} - T_{air})}{\Phi_{i,nom}} \quad (5)$$

where $\Phi_{i,nom}$ is the nominal incident solar power, ε is the thermal emittance, σ is the Stefan-Boltzmann constant, S is the external surface area of the receiver, T is the nominal surface temperature, h is the nominal convection coefficient in air, T_{air} is the nominal air temperature, and t_{os} is the “on-sun” time. The on-sun time only accounts for operation hours when the receiver is “on-sun”.

As an approximation, we assume the thermal efficiency as a function of the solar absorptance only, the other parameters being constant and determined by the plant data. This assumption is supported by the fact that the solar absorptance was shown as the main parameter that drives the thermal efficiency. The thermal emittance which has a smaller influence is assumed constant during the receiver's operation, as this data are normally unavailable. In case emittance data become available, the model can be readily upgraded.

A second assumption is made about the evolution of the solar absorptance itself. Little data are available that describes the absorptance of a coating over long periods of time (years). Accelerated aging tests are thus carried out in a solar furnace in order to estimate the initial rate at which the coatings' absorptance decreases. Then, the data are extrapolated with the aging trends discussed in [4]. The absorptance evolution is assumed to monotonously decrease from an initial value to a final value equal to the solar absorptance of the bare metal receiver (as if the coating had completely degraded at the end of life and bare metal receiver was unchanged throughout). The solar absorptance α_s and thermal emittance ε_T of the metallic substrate are $\alpha_s=0.9$ and $\varepsilon_T=0.8$ (Inconel 625).

3.2.1 Coating preparation

Inconel 625 is a Ni alloy that may be used for high temperature solar receivers [9,10]. All coatings described herein were deposited on square coupons of Inconel 625 measuring 5 cm×5 cm×2 mm.

Pyromark 2500 is one of the most common solar absorber black paint. Details on its composition, application and some data on its aging can be found in the literature [11,12]. Pyromark is coated and cured using an established protocol described by Ho et al. [13].

Lanthanum strontium manganite (LSM) oxide material crystallizes in the perovskite structure with the general formula ABO₃. Most LSM materials exhibit melting points in excess of 1000 °C [14,15]. LSM coatings are prepared via a thermal spray process as described in [16].

Co₃O₄ films were deposited onto Inconel coupons using electro-deposition from cobalt(II)-tartrate complexes [Co²⁺(tart)] in alkaline electrolyte by adapting a literature procedure [17]. Afterwards all samples are heated at 300 °C for 3 h to increase the crystallinity, as determined by X-ray diffraction.

Once coated, the coupons were put in an oven at 800 °C during 480 h. This first aging treatment aimed at stabilizing the coatings and placing them in a typical degrading phase (negative aging).

3.2.2 Characterization

The solar-weighted directional absorptance α_s is estimated using a hand-held SOC 410 Solar reflectometer, which measures the reflectance in seven spectral bands from 335 to 2500 nm at a 20° incidence angle. The solar weighted reflectance is calculated using an air mass index of 1.5 [13]. Hemispherical thermal emittance measurements (ε_T), are taken using an ET100 emissometer from Surface Optics Corporation weighted at 700 °C.

3.2.3 Accelerated testing

On-sun accelerated aging tests are conducted at the 16 kW solar furnace of the National Solar Thermal Test Facility at Sandia National Laboratories. This facility consists of a heliostat reflecting the solar rays towards a 6-m parabolic dish. The concentration ratio of the dish is about 5800. An attenuator made out of shutter blades enables the regulation of the incoming flux (see Fig. 1).

A sample support surrounded by a white protection panel is used (Fig. 2). A blower is set up on the back side of the samples to cyclically cool the material and generate thermal shocks (see Fig. 3). The convection coefficient is estimated at $h\approx 200$ W m⁻² K⁻¹. The attenuator and blower are controlled with a Labview module that enables automatic temperature cycles. Instrumentation, control and data acquisition are managed from the control room. Surface temperature, shutter opening, and weather data are monitored.

Each sample undergoes an aging treatment consisting of 150 cycles from 100 °C to 850 °C under an intermittent irradiance of 600 kW m⁻² ($\approx 10\%$ of full opening) to 0 kW m⁻². When the surface temperature reaches 850 °C, the attenuator closes while the blower turns on. The attenuator opens again when the surface temperature reaches 100 °C and the blower shuts off, and so forth. A solar-blind pyrometer is set up to measure the surface temperature of the sample. Fig. 4 shows typical irradiance and temperature cycles. The temperature derivative is also displayed as the “heating/cooling rate”. The temperature evolves from 100 °C to 850 °C at a maximum heating rate of about 130 °C s⁻¹ and a maximum cooling rate of 45 °C s⁻¹. These irradiance and temperature cycles correspond to some of the intense conditions a typical receiver may face in real operation.

The coating's thermal efficiency is monitored by measuring the solar absorptance and thermal emittance after every 10 cycles as described in the experimental section. As an approximation, the initial degradation rates are calculated by linear regression over the full 150 cycles.

Fig. 1. 16 kW solar furnace at the Sandia Laboratories NSTTF.

Fig. 2. Irradiated side. A protective white board allows concentrated radiation only on the test sample in the center. Residual concentrated light can be observed even when the shutter is fully closed.

Fig. 3. Back side of sample support with a blower cooling system.

3.3. Costs

Coating costs vary depending on the materials and coating techniques employed. Initial and reapplication costs are taken into account. Five categories are distinguished for the whole coating process: preparation of coating, preparation of substrate, application of coating, other treatments (ex: curing), and quality assurance.

Each category contains three cost subcategories: materials, equipment, and labor. Depending on the accuracy needed, other subcategories may be added to include other sources of expenses (transportation, safety, etc.). Different application techniques may be considered for the initial coating as well as for the following reapplications. The authors would like to emphasize that most of the provided estimates are virtual, due to the experimental nature of the LSM and Co_3O_4 coatings. Large cost assumptions were made, since some of the materials costs and deposition techniques have not been demonstrated at scale for CSP applications. In addition, aging tests were performed

Fig. 4. Solar irradiance, surface temperature and its derivative during irradiance cycles between 0 and 600 kW m^{-2} and temperature cycles between 100 and 850°C . The duration of one cycle is about 58 s.

on coatings that have not been completely optimized. As materials are developed, the models can be further optimized. The influence of a range of coating costs was discussed in [4].

Fig. 5. Evolution of the solar absorptance of Pyromark, Co₃O₄ and LSM deposited on Inconel 625 during the accelerated aging tests (150 cycles, 0–600 kW m⁻², 100 °C–850 °C).

4. Results

4.1. Evolution of the thermal efficiency

The solar absorptance measurements are shown in Fig. 5. Linear regressions give the initial solar absorptance and the initial degradation rate for each coating.

Pyromark has the highest initial absorptance at 0.955, followed by Co₃O₄ at 0.948 and LSM at 0.941. Pyromark also has the lowest initial degradation rate at $-1.90 \times 10^{-6} \text{ cy}^{-1}$. Co₃O₄ initially degrades the fastest with a rate of $-1.86 \times 10^{-5} \text{ cy}^{-1}$. LSM has an initial degradation rate of $-9.00 \times 10^{-6} \text{ cy}^{-1}$. It is worthwhile to note that the behavior of the coatings may change slightly depending on the substrate choice, i.e. durability or optical properties of coatings on Inconel may differ than those deposited on stainless steel or Haynes. We invite the reader to be cautious referring to these measurements which aim to demonstrate the evaluation method of LCOE gain rather than provide high accuracy characterization of the experimental coatings themselves.

The initial degradation rates in the unit time “on-sun” (“on-sun year”, osyr) are calculated with an equivalence relation between the number of aging cycles and the “on-sun” aging time. In [4], the degradation rate of Pyromark on Solar One receivers was estimated at $-0.0482 \text{ osyr}^{-1}$. One on-sun day would thus generate a similar degradation to 69 accelerated aging cycles. This estimation being associated with large uncertainties, an equivalence of 10 testing cycles is conservatively assumed. The objective is to feed the model with a plausible absorptance evolution although uncertainties exist. Refining the model will be possible through an iterative process when additional aging data are made available.

Table 3 shows the initial optical properties assumed in the model. Thermal emittance is measured for the calculation of the thermal efficiency and is assumed constant (see Section 3.2). LSM has the lowest emittance at 0.782, before Co₃O₄ at 0.785 and Pyromark 0.879.

Table 3

Initial solar absorptance, thermal emittance, and initial linear degradation rates of Pyromark 2500, LSM and Co₃O₄. The substrate is made of Inconel 625.

	Initial absorptance (-)	Emittance (-)	Initial degradation rate (cy ⁻¹)	Initial degradation rate (osyr ⁻¹)
Pyromark	0.955	0.879	-1.90×10^{-6}	-0.0260
LSM	0.941	0.782	-9.00×10^{-6}	-0.1233
Co3O4	0.948	0.785	-1.86×10^{-5}	-0.2548

Fig. 6. Estimated thermal efficiency evolution of Pyromark, Co₃O₄ and LSM coatings.

Fig. 7. Estimated solar absorptance evolution of Pyromark, Co₃O₄ and LSM coatings with associated uncertainties on the initial value, the initial and the end-of-life absorptance values.

The evolution of the thermal efficiency is plotted in Fig. 6. LSM and Co₃O₄ behave similarly, differing from that of Pyromark with smaller initial degradation rates and lower emittance values, causing a higher “end-of-life” thermal efficiency. After 2.7 years, Pyromark has the lowest thermal efficiency if no reapplication is performed.

In order to account for uncertainties on the thermal efficiency evolution, a $\pm 1\%$ error on the initial and end-of-life solar absorptance values is analyzed, as well as a similar error on the thermal emittance. Initial degradation rates half and twice the estimated value are also investigated, as well as downtimes twice smaller and larger. The corresponding extrapolated evolutions are plotted in Figs. 7 and 8.

4.2. Cost estimates

4.2.1. Pyromark

The cost of Pyromark is detailed in Table 4. It includes the initial application and possible reapplications at a frequency (or reapplication interval) determined by the operating company. For each application, materials, equipment and labor categories are distinguished. These numbers are supported by previous cost estimations for Pyromark [3,4] in similar conditions. However, variations up to an order of magnitude could reasonably be expected, depending on the coating quality required.

Fig. 8. Solar absorptance of Pyromark, Co₃O₄ and LSM coatings with associated uncertainties on the initial degradation rate (a), the end-of-life absorptance (b), and the thermal emittance (c).

4.2.2. LSM

The cost of the thermal spray coating shown in Table 5 accounts for the use of a spray torch to perform the initial coating. A laser-treatment is assumed available to “restore” the coating properties without having to recoat. Reapplication costs are thus relatively low (\$62 k).

4.2.3. Co₃O₄

The costs of the Co₃O₄ are estimated assuming the need for an electroplating bath to coat and recoat the receiver. Large-scale electro-deposition is a challenge, and costs may vary by a large amount depending on available technology to perform this task. Table 6 summarizes the cost details and totals.

4.3. LCOE gain and efficiency

$LCOE_{ref}$ is calculated based on an uncoated receiver of oxidized Inconel 625 (see Section 3.2). We obtain $LCOE_{ref} = \$253.63 \text{ MW}^{-1} \text{ h}^{-1}$ and $LCOE_{id} = \$187.99 \text{ MW}^{-1} \text{ h}^{-1}$. The difference between these two terms gives $(\Delta LCOE)_{id} = -\$65.64 \text{ MW}^{-1} \text{ h}^{-1}$. From there, the LCOE gain due to the coating and LCOE efficiency can be computed for the three coatings. $(\Delta LCOE)_c$ is plotted as a function of the reapplication interval on Figs. 9–12. The dashed curves correspond to the associated uncertainties on the input parameters.

For very short reapplication intervals, $(\Delta LCOE)_c$ is positive which means the high reapplication costs increase the LCOE of the plant more than the high thermal efficiency decreases it. As soon as $RI > 0.3$ years, $(\Delta LCOE)_c$ becomes negative for all coatings, meaning the three coatings contribute to reducing the LCOE of the plant thanks to a high thermal efficiency. A minimum value of $(\Delta LCOE)_c$ is found for a relatively short reapplication interval of one year or less. It corresponds to the optimal reapplication interval that provides the lowest LCOE.

Of the three coatings, Pyromark is the one that achieves the lowest LCOE gain value of $-\$11.97 \text{ MW}^{-1} \text{ h}^{-1}$ for a reapplication interval of 1.0 years. This is a 4.7% reduction relative to the reference LCOE of $\$253.63 \text{ MW}^{-1} \text{ h}^{-1}$. The LCOE gain efficiency of Pyromark is $\eta_{(\Delta LCOE)_c} = -11.97 / -65.64 = 0.182$.

The LSM coating achieves the second best LCOE reduction with a minimum $(\Delta LCOE)_c$ of $-\$9.13 \text{ MW}^{-1} \text{ h}^{-1}$ ($\eta_{(\Delta LCOE)_c} = 0.139$) at $RI = 0.6$ years. The shorter optimal reapplication interval is due to lower reapplication costs. The lowest $(\Delta LCOE)_c$ achieved with Co₃O₄ is $-\$5.44 \text{ MW}^{-1} \text{ h}^{-1}$ ($\eta_{(\Delta LCOE)_c} = 0.083$) at $RI = 1$ years. The “wavy” features observed on the curves at longer RI appear due to the savings made when the last maintenance reapplication would fall on the end-of-life year (30th in this case). No reapplication is assumed for this last year.

If no reapplication is performed at all (i.e. $RI = 30$ years), we observe that both LSM and Co₃O₄ achieve lower LCOE gain values than Pyromark ($-\$1.78 \text{ MW}^{-1} \text{ h}^{-1}$ and $-\$1.33 \text{ MW}^{-1} \text{ h}^{-1}$ vs. $-\$0.48 \text{ MW}^{-1} \text{ h}^{-1}$, respectively).

The initial solar absorptance value has a considerable impact on $(\Delta LCOE)_c$. As shown on Fig. 9 by the dashed curves, a 1% increase in the initial absorptance of Pyromark leads to a $-\$2.92 \text{ MW}^{-1} \text{ h}^{-1}$ reduction of the minimum LCOE achievable (at $RI = 1.0$ year). With an initial absorptance 1% higher for Co₃O₄ and 1% lower for LSM, the Co₃O₄ coating would slightly outperform LSM and achieves a lower LCOE. The low costs and higher absorptance of Pyromark 2500 give it a strong advantage over the two other more selective coatings.

Fig. 10 shows the effect of a $\pm 1\%$ error on the end-of-life absorptance. For Pyromark, this error does not modify the minimum LCOE gain. For LSM, and especially Co₃O₄, the effect is more significant. The minimum LCOE gain of LSM and Co₃O₄, observed with a $+1\%$ end-of-life absorptance is $-\$4.12 \text{ MW}^{-1} \text{ h}^{-1}$ at $RI = 3.4$ years and $-\$3.23 \text{ MW}^{-1} \text{ h}^{-1}$ for $RI = 30$ years, respectively. This means any reapplication of the Co₃O₄ coating would be less cost-effective than no reapplication. With a 1% lower end-of-life absorptance, the results are quite different. The Co₃O₄ coating would increase the LCOE regardless of the reapplication interval. Fig. 11 emphasizes the influence of uncertainty on the initial degradation rate that was experimentally determined (see Section 3.2). The initial degradation rate strongly impacts $(\Delta LCOE)_c$. It does not modify significantly the optimal RI for Pyromark and LSM but does shift that of Co₃O₄ coating from $RI = 30$ years—twice the higher rate—to $RI = 4.4$ years with a half initial degradation rate. The minimum LCOE gains are sensitive to the initial degradation rate for all three coatings. Variations of about $\pm \$0.8 \text{ MW}^{-1} \text{ h}^{-1}$ for Pyromark, $\pm \$1.7 \text{ MW}^{-1} \text{ h}^{-1}$ for LSM and $\pm \$2.6 \text{ MW}^{-1} \text{ h}^{-1}$ for Co₃O₄ are observed.

Fig. 12 shows that a $\pm 1\%$ error on the thermal emittance is not negligible but has a relatively low influence on the LCOE gain compared to that of the initial absorptance (about 10 times lower). Fig. 13 shows the effect of a twice higher and twice lower reapplication

Table 4

Initial and reapplication costs for Pyromark 2500.

Pyromark 2500	Initial costs (\$)	Comments	Reapplication costs (\$)	Comments
Preparation of coating	26,804		25,304	
Materials	12,804	Pyromark+solvent	12,804	Pyromark+solvent
Equipment	2000	Containers, cleaning, misc.	500	Existing equipment, consumables
Labor	12,000	120 h, 100\$/h	12,000	120 h, 100\$/h
Preparation of substrate	37,635		28,135	
Materials	7896	Sand \$5 per m ²	7896	Sand \$5 per m ²
Equipment	10,000	Sandblasting rig, scaffolding equipment, safety gears	500	Existing equipment, consumables
Labor	19,739	1/8 h per m ² per people	19,739	1/8 h per m ² per people
Application of coating	24,739		20,239	
Materials	0		0	
Equipment	5000	Compressor, exhaust system, misc.	500	Existing equipment, consumables
Labor	19,739	1/8 h per m ² per people	19,739	1/8 h per m ² per people
Curing and other treatments	112,000		12,500	
Materials	0		0	
Equipment	100,000	Custom oven	500	
Labor	12,000	120 h, 100\$/h	12,000	3 people, 1 week
Quality assurance, performance monitoring	62,000		7700	
Materials	0		0	
Equipment	50,000	Reflectometer, cameras, computers, misc.	500	Maintenance of instrumentation
Labor	12,000	120 h, 100\$/h	7200	72 h, 100\$/h
Total	263,178		93,878	
Total annualized	8773		3129	

downtime (*DT*). At lower *DT*s, it is possible to achieve a lower LCOE by reducing the reapplication interval. The optimal *RI* shifts from 2.0 year to 1.5 year with Pyromark, from 2.0 year to 1.2 year with LSM, and from 10 year to 2.5 year with Co₃O₄. Thus, reducing the receiver downtime for recoating allows for an increase in the reapplication frequency and a decrease of the LCOE. Two additional aspects need to be considered here: 1) a reduction of *DT* could also lead to lower labor costs but it is not taken into account here; 2) the cost for material disposal are not taken into account. They might be significant depending on the materials and consumables used.

5. Conclusion

Absorber coatings are generally developed, ranked, and selected according to their maximum thermal efficiency, disregarding cost, durability and operating conditions. Although such an approach might be valid for continuous and steady energy conversion processes, it is less relevant for intermittent and transient processes where material aging occurs. The levelized cost metric is used through the development of the LCOE gain as a systems approach. LCOE gain calculations were applied to three different coatings: Pyromark 2500, lanthanum stront-

Table 5

Initial and reapplication costs for LSM.

LSM	Initial costs (\$)	Comments	Reapplication costs (\$)	Comments
Preparation of coating	165,914		0	
Materials	157,914	100\$/m ² for powder+gas	0	
Equipment	5000	Containers, misc.	0	
Labor	3000	30 h, 100\$/h	0	
Preparation of substrate	47,635		10,370	
Materials	7896	Sand \$5 per m ²	0	Sand \$5 per m ²
Equipment	20,000	Sandblasting rig, scaffolding equipment, compressor, safety gears	500	Basic cleaning tools
Labor	19,739	1/8 h per m ² per people	9870	Rapid cleaning 1/16 h per m ² per people
Application of coating	49,478		0	
Materials	0		0	
Equipment	10,000	Rental torch, tubes, masks, compressor, exhaust fans, etc.	0	Rental torch, tubes, masks, compressor, exhaust fans, etc.
Labor	39,478	1/4 h per m ² per people	0	1/4 h per m ² per people
Curing and other treatments	44,478		44,478	
Materials	0		0	
Equipment	5000	Rental laser	5000	Rental laser
Labor	39,478	1/4 h per m ² per people	39,478	1/4 h per m ² per people
Quality assurance, performance monitoring	62,000		7700	
Materials	0		0	
Equipment	50,000	Reflectometer, cameras, computers, misc.	500	Maintenance of instrumentation
Labor	12,000	120 h, 100\$/h	7200	72 h, 100\$/h
Total	369,505		62,548	
Total annualized	12,317		2085	

Table 6
Initial and reapplication costs for Co_3O_4 .

Co_3O_4	Initial costs (\$)	Comments	Reapplication costs (\$)	Comments
Preparation of coating	89,957		89,957	
Materials	78,957	Co, nitrate, sodium tartrate, 50\$/m ²	78,957	Co, nitrate, sodium tartrate, 50 \$/m ²
Equipment	5000	Containers, misc.	5000	Containers, misc.
Labor	6000	60 h, 100\$/h	6000	60 h, 100\$/h
Preparation of substrate	47,635		125,635	
Materials	7896	Sand \$5 per m ²	7896	Sand \$5 per m ²
Equipment	20,000	Sandblasting rig, compressor, safety gears	50,000	Receiver unmount+re-mount
Labor	19,739	1/8 h per m ² per people	67,739	240 h×2+1/8 h per m ² per people
Application of coating	541,000		91,000	
Materials	5000	Nitrogen	5000	Nitrogen
Equipment	500,000	Plating bath (custom size)+cranes	50,000	Maintenance
Labor	36,000	+energy+gears	36,000	360 h, 100\$/h
Curing and other treatments	112,000		13,000	
Materials	0		0	
Equipment	100,000	Custom oven	1000	Maintenance
Labor	12,000	120 h, 100\$/h	12,000	120 h, 100\$/h
Quality assurance, performance monitoring	62,000		7700	
Materials	0		0	
Equipment	50,000	Reflectometer, cameras, computers, misc.	500	Maintenance of instrumentation
Labor	12,000	120 h, 100\$/h	7200	72 h, 100\$/h
Total	852,592		327,292	
Total annualized	28,420		10,910

Fig. 9. LCOC of Pyromark, LSM, and Co_3O_4 as a function of the reapplication interval. The dashed curves correspond to a $\pm 1\%$ uncertainty on the initial solar absorptance. $\text{LCOE}_{\text{ref}} = \$253.63 \text{ MW}^{-1} \text{ h}^{-1}$.

Fig. 11. LCOC of Pyromark, LSM, and Co_3O_4 as a function of the reapplication interval. The dashed curves correspond to initial degradation rates half and twice as estimated.

Fig. 10. LCOC of Pyromark, LSM, and Co_3O_4 as a function of the reapplication interval. The dashed curves correspond to $\pm 1\%$ uncertainty on the end-of-life solar absorptance.

Fig. 12. LCOC of Pyromark, LSM, and Co_3O_4 as a function of the reapplication interval. The dashed curves correspond to $\pm 1\%$ uncertainty on thermal emittance.

Fig. 13. LCOC of Pyromark, LSM, and Co_3O_4 as a function of the reapplication interval. The dashed curves correspond to an estimated reapplication downtime multiplied and divided by 2, respectively.

tium manganite and Co_3O_4 . Estimates of the LCOE reduction due to the receiver coating were calculated, accounting for efficiency, cost, durability and management (operation and maintenance). This study shows that Pyromark potentially achieves a higher LCOE reduction than LSM and Co_3O_4 , even with their higher selectivity. The introduction of the LCOE gain efficiency attributes Pyromark 2500 a value of 0.182. The LCOE gain efficiency of LSM is calculated at 0.139; that of Co_3O_4 is estimated at 0.083. These values are case-specific and were obtained assuming a 100 MW_e solar power tower. The reapplication interval, depending on cost and receiver downtime, can be adjusted to minimize the LCOE. Corresponding optimal reapplication intervals range between 0.5 and 2.5 years. The thermal efficiency—mainly driven by the solar absorptance—is a key parameter. Depending on its evolution, LSM might be more cost-effective than Pyromark if LSM achieves a 1% higher absorptance or demonstrates a lower initial degradation rate ($< 2 \times 10^{-6} \text{ cycle}^{-1}$). Co_3O_4 could outperform current LSM, provided an electrodeposition technique is available at large scale and for a reasonable cost ($< \$1 \text{ M}$ per application). As the aging of the three coatings is evaluated based on short time accelerated aging tests, uncertainties may be diminished with additional aging tests. Accelerated testing at the month scale is also recommended in order to refine the LCOE gain results with firm trends.

At the moment of writing, no solar coating has demonstrated significantly higher cost-effectiveness than Pyromark to the authors' knowledge, especially because solar selectivity is difficult to achieve at high temperature (shift towards shorter wavelengths) and often vanishes due to aging processes. A possible way forward would be the development of non-selective high temperature ultra-black coatings. On the other hand, uncoated receivers that achieve high solar absorptivity through geometry, surface features (fractal receivers [18]) and oxidation properties (highly absorptive oxidized metal) are also serious options to consider. As an outlook, this work shows that the cost-effectiveness of solar absorber coatings is a complex notion, strongly dependent on the local environment and operating conditions.

Even though future performance and general costs are hardly predictable, successful solar absorber materials will be those developed and optimized with a systems approach.

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References

- [1] M. Köhl, B. Carlsson, G.J. Jorgensen, A.W. Czanderna, *Performance and Durability Assessment—Optical Materials for Solar Thermal Systems*, Elsevier, Oxford, 2004.
- [2] A. Boubault, B. Claudet, O. Faugeron, G. Olalde, J.-J. Serra, A numerical thermal approach to study the accelerated aging of a solar absorber material, *Sol. Energy* 86 (2012) 3153–3167. <http://dx.doi.org/10.1016/j.solener.2012.08.007>.
- [3] C.K. Ho, J.E. Pacheco, Levelized cost of coating (LCOC) for selective absorber materials, *Sol. Energy* 108 (2014) 315–321. <http://dx.doi.org/10.1016/j.solener.2014.05.017>.
- [4] A. Boubault, C.K. Ho, A. Hall, A. Ambrosini, T.N. Lambert, Levelized cost of energy (LCOE) metric to characterize solar absorber coatings for the CSP industry, *Renew. Energy* 85 (2016) 472–483.
- [5] Organisation for Economic Co-operation and Development (OECD), *Green Growth Studies*, 2011.
- [6] United Nations Environment Programme (UNEP), *Towards a Life Cycle Sustainability Assessment: Making Informed Choices on Products*, 2011.
- [7] International Renewable Energy Agency, *Renewable Energy Technologies: Cost Analysis Series*, vol. 1, Power Sector, Issue 2/5, 2012.
- [8] NREL, *Transparent Cost Database*, 2014.
- [9] G.J. Kolb, An Evaluation of Possible Next-generation High-temperature Molten-Salt Power Towers, Sandia National Laboratories, SAND2011-9320, 2011.
- [10] Clifford K. Ho, Brian D. Iverson, Review of high-temperature central receiver designs for concentrating solar power, *Renew. Sustain. Energy Rev.*, vol. 29, January 2014, pp. 835–846, ISSN 1364-0321, (<http://dx.doi.org/10.1016/j.rser.2013.08.099>).
- [11] A. Boubault, B. Claudet, O. Faugeron, N. Guerin, G. Olalde, Study of the aging of a solar absorber material following the evolution of its thermoradiative and thermophysical, *High Temp. – High Press.* 2 (5) (2013) 405–420.
- [12] A. Boubault, B. Claudet, O. Faugeron, G. Olalde, Aging of solar absorber materials under highly concentrated solar flux, *Sol. Energy Mater. Sol. Cells* 123 (2014) 211–219.
- [13] C.K. Ho, A.R. Mahoney, A. Ambrosini, M. Bencomo, A. Hall, T.N. Lambert, Characterization of Pyromark 2500 paint for high-temperature solar receivers, *J. Sol. Energy Eng.* 136 (1) (2013) 014502–014502.
- [14] Oerlikon Metco, Material Safety Data Sheet, Lanthanum Strontium Manganite (LSM) Powder, Metco 6800 n.d., (https://www.oerlikon.com/ecomaXL/files/metco/oerlikon_DSMTS-0024.4_LSM.pdf) (Accessed 9 April 2016).
- [15] J.R. Davis, *Handbook of Thermal Spray Technology*, ASM International, USA, 2005.
- [16] A. Ambrosini, T.N. Lambert, A. Boubault, A. Hunt, D.J. Davis, D. Adams, A.C. Hall, Thermal stability of oxide-based solar selective coatings for CSP central receivers, in: *Proceedings of the ASME 9th International Conference on Energy Sustainability*, ES 2015, collocated with the ASME 2015 Power Conference, the ASME 2015 13th International Conference on Fuel Cell Science, Engineering and Technology, and the ASME 2015 Nuclear Forum, 1, 2015.
- [17] J.A. Koza, Z. He, A.S. Miller, J.A. Switzer, Electrodeposition of crystalline Co_3O_4 —a catalyst for the oxygen evolution reaction, *Chem. Mater.* 24 (2012) 3567–3573. <http://dx.doi.org/10.1021/cm3012205>.
- [18] J. Yellowhair, C.K. Ho, J.D. Ortega, J.M. Christian, C.E. Andracka, Testing and optical modeling of novel concentrating solar receiver geometries to increase light trapping and effective solar absorptance, *Proc. SPIE* 9559, High and Low Concentrator Systems for Solar Energy Applications X, 95590A, 2015 (<https://dx.doi.org/10.1117/12.2186647>).