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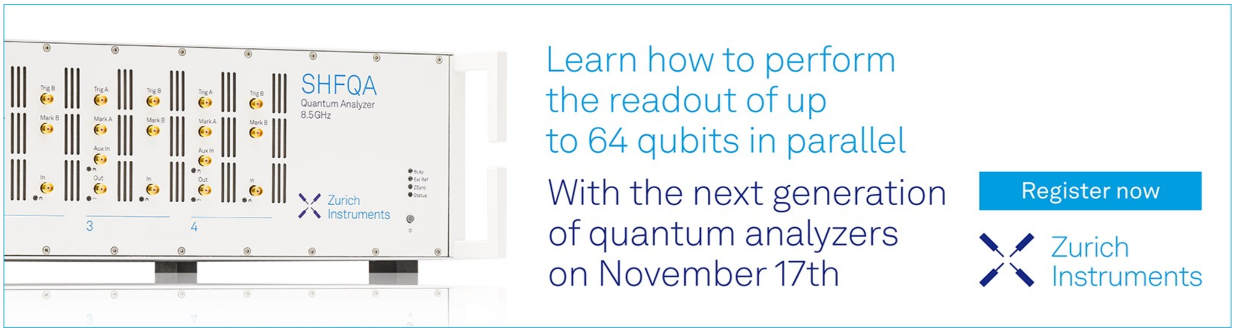

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Techno-Economic Assessment of New Material Developments in Central Receiver Solar Power Plants

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Abstract. For the evaluation of functional material developments in the EU-project RAISELIFE, a tool chain of ray tracing, thermal FEM simulation and dynamic system simulation has been created. Multi-year simulations allow considering degradation of optical parameters. With this tool chain, the thermal energy output of a reference plant with one non-selective and one generic selective coating was simulated. The LCOE (Levelized Cost of Electricity) was calculated based on these results. The LCOE of the selective coating is 2.6 % lower, if the same costs are assumed. Furthermore, the ideal recoating interval for the reference system was identified. Finally, it was demonstrated that dynamic system simulation shows benefits to evaluate in-service performance of functional materials as dynamic behavior of solar thermal power plants can change quite significantly, if another coating is used.

INTRODUCTION

To increase the power output of solar thermal power plants over the full life time, it is essential to focus on the improvement of functional materials such as mirror coatings, selective and non-selective receiver coatings, as well as corrosion resistant steel and coatings to use with molten salt. The EU-funded project RAISELIFE focuses on raising the lifetime of these key functional materials. Materials are being developed and tested with accelerated aging tests to obtain information about degradation mechanisms. A simulation tool chain has been developed to quantify the impact of the results of the RAISELIFE project in plant operation. For example this tool chain enables the annual performance comparison of selective and non-selective receiver coatings. Simulation results can then be used to perform economic assessments. For this purpose Levelized Cost of Electricity (LCOE) is calculated for the RAISELIFE reference plant, a 150 MW CRS plant in Morocco. The costs will be put in relation to the resulting annual yield. The impact of a selective coating on the LCOE is evaluated in this paper. Also simulations with different recoating intervals are performed to identify the minimum LCOE. At the same time the benefit of dynamic system simulation for the evaluation of functional material is pointed out.

METHODOLOGY

The economic evaluation of material developments is an important aspect of the RAISELIFE project. In this paper the RASIELIFE approach is explained by looking at receiver coating developments.

To be able to compare the material developments, each material is virtually applied on a predefined reference power plant model. Dynamic system simulation is performed with a tool chain including the Fraunhofer raytracing software Raytrace 3D, the DLR FEM thermal efficiency simulation software Astrid as well as the Fraunhofer system simulation software ColSim CSP. The software is further described below. Multi-year simulations are performed to be able to take degradation mechanisms as well as replacement and recoating procedures into account. In a second step the LCOE can be calculated based on the simulation results.

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The simulation results are than compared to results obtained with an alternative calculation method introduced by Ho [1] that uses constant system parameters in order to assess receiver coatings. This method is also explained here.

Optical Simulation with Raytrace3D

The ray tracing software Raytrace3D developed by Fraunhofer ISE calculates the flux distribution on absorber surfaces with high spatial resolution. Reflections from the receiver tubes towards the environment or to other tubes are considered. All relevant optical effects like cosine losses, shading, absorption on heliostats, blocking, spillage, atmospheric attenuation and reflection on the receiver surfaces are taken into account. With the help of a sky discretization approach [2], the transient distribution of concentrated radiation on the receiver surfaces is calculated in the form of flux maps depending on sun position and receiver load. These act as an input to the thermal receiver model and system simulation. Another SolarPACES 2018 paper describes this approach in more detail [3].

Thermal Receiver Model ASTRID©

With the ASTRID© approach by DLR [4], the thermal efficiency of the receiver is simulated. The previously described flux maps are input to this FEM model, defining the radiation boundary conditions. One dimensional fluid flow elements are used to model the heat transfer to the fluid. Local heat transfer coefficients are implemented as a function of the local fluid temperature, the Reynolds number is calculated based on the Gnielinksi correlation and the radiosity method [5] is used to describe the thermal radiation exchange between absorber tubes, insulation and ambient. For absorber tubes, insulation and heat transfer fluid, the local temperatures are obtained. Based on these temperatures, the thermal receiver efficiency is calculated with the thermal losses by long-wave radiation, convection and conduction. The thermal efficiency depending on different load cases is input to the system simulation in ColSim CSP.

ColSim CSP Dynamic System Simulation

The Fraunhofer ISE simulation software ColSim [6] performs fast dynamic system simulations with an adjustable level of detail. For the RAISELIFE project, one minute time steps are being used. The tool is optimized for solar thermal power plants and solar thermal process heat applications. All relevant components of the reference system like heliostat field and receiver, HTF pump, thermal energy storage and power block are part of an extensive library of detailed component models. Transient effects and operational constraints like mass flow and temperature limitations are considered. This enables the simulation of solar field and power block start-up and shut-down. For the project RAISELIFE, degradation mechanisms of functional material parameters as well as downtime due to maintenance or replacement of components have been implemented. To evaluate the system behavior including degradation over the full life time of a plant, multi-year simulations are performed. The operation and storage dispatch strategy aims at producing electricity at design load as often as possible. The energy output of annual as well as multi-year simulations can be used to perform feasibility studies and assess the system design and performance.

The reference CRS power plant located in Ouarzazate, Morocco has a gross electricity output of 150 MW, thermal power of 600 MW and about 4.5 hours of storage. The system layout is shown in **FIGURE 1**. The heliostat field consists of 72,000 heliostats of 20.8 m².

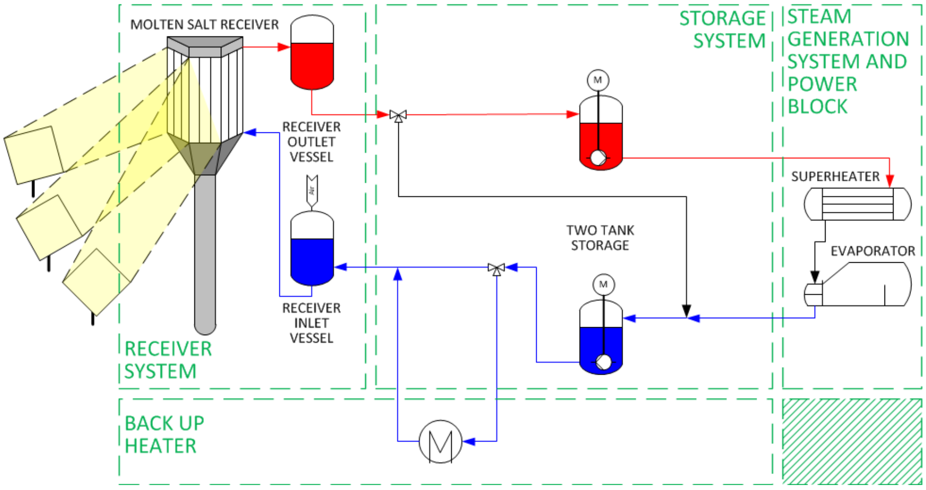

FIGURE 1. System layout of the RAISELIFE CRS reference plant

Alternative to Calculate Thermal Performance Change without Simulation

The simulation results for thermal power output obtained with dynamic system simulation are compared to the results obtained with a static method. The alternative way to calculate the system performance was introduced by Ho [1] in his paper on "Leveliced Cost of Coatings for Selective Absorber Materials". Here constant collection and absorber efficiencies are used, as the following formula shows:

$$\mathrm{E}_{\text{thermal}} = \mathrm{G}_{\text{bn,annual}} \cdot \mathrm{A}_{\text{ap}} \cdot \eta_{\text{absorber}} \cdot \eta_{\text{collection}} - \mathrm{E}_{\text{degradation}} - \mathrm{E}_{\text{downtime}} \tag{1}$$

with:

$\mathrm{G}_{\text{bn,annual}}$	Annual direct normal irradiation
A_{ap}	Aperture area of heliostat solar field
η_{absorber}	Efficiency of selective absorber that considers absorptance and emittance of material
$\eta_{\text{collection}}$	Thermal collection efficiency that accounts for cosine losses, availability, heliostat defocusing, mirror reflectivity, blocking and shading, atmospheric attenuation, spillage, startup losses, convection, conduction, and receiver piping losses, but not absorptance and emittance of material
$\mathrm{E}_{\text{degradation}}$	Thermal energy lost due to degradation
$\mathrm{E}_{\text{downtime}}$	Thermal energy lost due to downtime of the plant during replacements

Here η_{absorber} is calculated with the following equation [1]:

$$\eta_{\text{absorber}} = \frac{\alpha_S \cdot Q - \epsilon \cdot \sigma \cdot \mathrm{T}^4}{Q} \tag{2}$$

with:

α_S	Solar absorptance
ϵ	Thermal emmitance
σ	Stefan-Boltzmann constant ($5.67 \cdot 10^{-8}\ W/m^2K^4$)
Q	Irradiance on the receiver

Economic Assessment with LCOE

To evaluate the simulation results, the Levelized Cost of Electricity (LCOE) is calculated based on the equation below [7].

$$\mathrm{LCOE} = \frac{C_{capex} + \sum_{t=1}^{T} \frac{C_{opex,t} + C_{replex,t}}{(1+i)^t}}{\sum_{t=1}^{T} \frac{E_t}{(1+i)^t}} \tag{3}$$

with:

C_{capex}	Total investment costs
T	Lifetime of plant
t	Year of plant operation
$C_{opex,t}$	Operation & maintenance costs
$C_{replex,t}$	Replacement and recoating costs
E_t	Annual electricity yield
i	Interest rate

For this overall investment costs of 400 million US$ are used. For the herein presented example, annual operation & maintenance costs are assumed to be 1 % of the investment costs. This is summarized in **TABLE 1**.

TABLE 1. Cost assumptions for LCOE evaluation of RAISELIFE reference plant

Parameter	**Unit**	**Value**
Total investment costs	$	400,000,000
Operation & Maintenance	% of investment costs/a	1
Interest rate	%	7
Lifetime	a	30

Also the reapplication costs for receiver coating are taken into account. In this paper the RAISELIFE approach is shown on the example of one selective and one non-selective coating. **TABLE 2** shows the cost assumptions for coating and application costs from the RAISELIFE project, which are based on industry experience.

TABLE 2. Cost assumptions for economic assessment of RAISELIFE receiver coatings

Parameter	**Costs in $**
Coating material cost	700,000
Initial application cost	1,000,000
Reapplication costs (at height of receiver)	2,000,000

RESULTS AND DISCUSSION

Impact of Selective Coating Use on LCOE

The non-selective coating of the reference plant is characterized by an absorptance of 95 % and an emittance of 91 %. The plant life time is assumed to be 30 years. Degradation of the coating absorptance of 0.5 % per year is considered. The absorptance loss takes place linearly over time. Every eight years the receiver is recoated. In the simulation the absorptance is then reset to its initial value. The recoating process is combined with a downtime of 12 days.

Dynamic system simulation is performed for 30 consecutive years. The annual thermal receiver yield is shown in **FIGURE 2**. The dotted line shows the thermal yield of 1499 GWh that the plant would produce, if no degradation and recoating would be considered. The continuous line shows the yield, if degradation is taken into account. The yield reduces every year by approximately 0.24%, which is significantly less reduction than the annual 0.5 % reduction of absorptance due to degradation. There is no proportional correlation between absorptance and receiver output. This is due to the fact that the heliostat field is rather large in contrast to the thermal power of the receiver which leads to a lot of defocusing, especially around noon, when irradiation reaches its peak level. In these periods, the deterioration of optical coating parameters by degradation have less impact on the energy output, as higher losses can be compensated by focusing "excess" heliostats on the receiver. Every eighth year, the receiver is recoated. Even if in this year the absorptance regains its initial value, the downtime of 12 days, in which the plant cannot be operated, leads to the lowest annual yield of 1454 GWh. The mean annual thermal yield throughout the full lifetime is 1484 GWh/a. The mean annual electrical yield is 575 GWh/a.

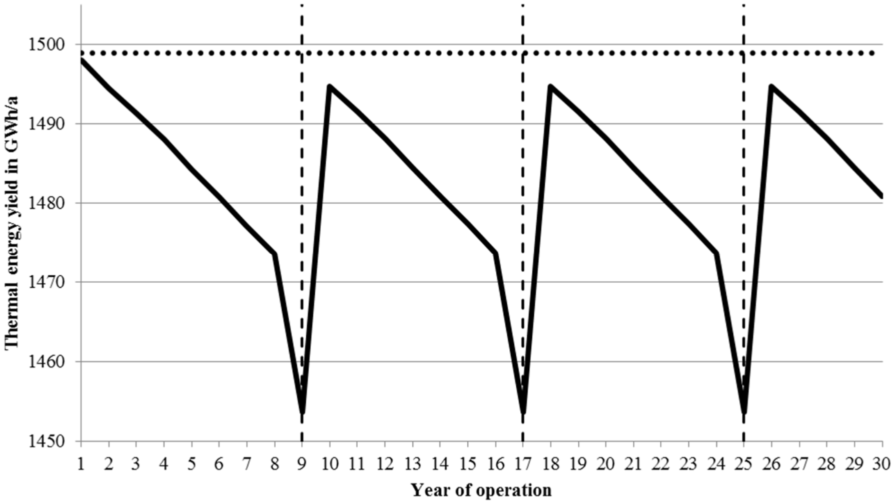

FIGURE 2. Thermal energy yield of receiver depending on year of lifetime

The LCOE for the reference system with non-selective coating based on the cost parameters in the introduction chapter is 6.34 $Ct/kWh.

The same simulation has been performed with a generic selective receiver coating with emittance of 40 % while the absoptance stays at 95 %. The mean annual electricity yield increased by 2.8% to 591 GWh per year. If the costs are assumed to be the same, the LCOE results to 6.17 $Ct/kWh. The LCOE reduction that can be reached by using a selective coating (that has same cost and degradation curve as non-selective coating) is 2.7 %.

Optimization of Recoating Interval

The tool chain also enables the assessment of operation strategies, like the impact of recoating intervals on the plant's economic profitability. To find the best recoating interval, the LCOE for different simulation scenarios is compared. Simulations for recoating intervals of 3 years (9 reapplications), 5 years (5 reapplications), 8 years (3 reapplications), 15 years (1 reapplication) and >30 years (no reapplication) are conducted. The LCOE is calculated for each simulation case, considering the cost assumption listed in **TABLE 1**. Reapplication costs are listed in **TABLE 2**.

The result of the assessment is shown in **FIGURE 3**. While the mean annual yield is the highest for five reapplications in a lifetime of 30 years (recoating interval of five years), the LCOE is the lowest for three reapplications (recoating interval of eight years). From an economic point of view the optimal recoating interval is therefore eight years. Compared to the case with no reapplication at all, the LCOE could be reduced by 2.1 %.

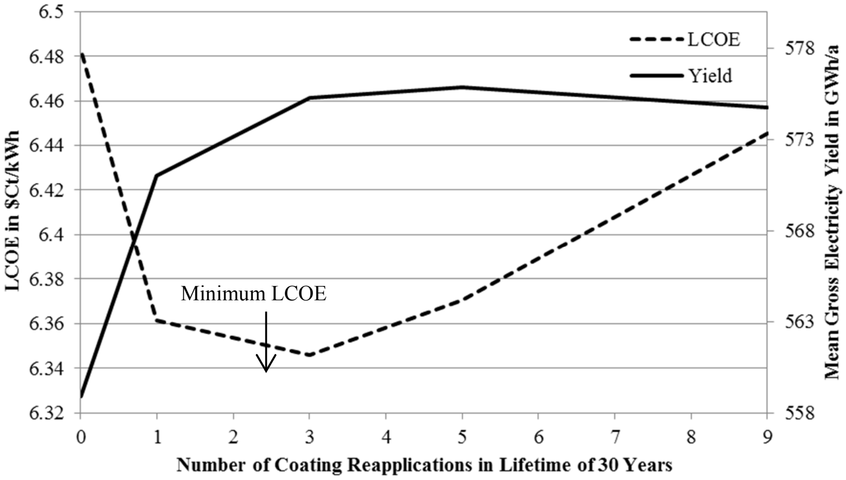

FIGURE 3. Influence of number of replacements in 30 year life time on LCOE and mean annual yield

Benefit of Dynamic System Simulation for Material Development Assessment

New receiver coatings have an impact on the receiver thermal output that directly correlates with the electrical output. A static approach with mean annual parameters to determine the annual thermal energy yield has been introduced in the methodology chapter. This static approach is compared to the method using dynamic system simulation, to demonstrate the effect on the assessment of material developments in real plant operation. Degradation and reapplication of absorber coatings were neglected to reduce the influencing factors on this investigation.

The plant with reference coating (absorptance 95 %, emittance 91 %) is used as base case. The main parameters that describes the behavior of a plant in the static approach is the thermal collection efficiency $\eta_{\text{collection}}$ and the absorber efficiency η_{absorber}. The former includes all optical effects of the heliostat field as well as defocusing and other operational restrictions. This value could be assumed, extracted from measurements or determined with the help of simulations. The choice of thermal collection efficiency mainly defines how good the match of the results compared to dynamic system simulation is.

The absorber efficiency η_{absorber} is calculated based on the equation introduced by Ho with absorptance of 95 %, emittance of 91 %, irradiance on receiver Q of 460 kW/m² and temperature of 700 °C (973.15 K):

$$\eta_{\text{absorber,non-selective}} = \frac{\alpha_S \cdot Q - \epsilon \cdot \sigma \cdot \mathrm{T}^4}{Q} = \frac{0.95 \cdot 461{,}000 - 0.91 \cdot 5.67 \cdot 10^{-8} \cdot 973.15^4}{461{,}000} = 0.850 \qquad (4)$$

Then the thermal collection efficiency $\eta_{\text{collection}}$ can be calculated from the simulated thermal energy yield $E_{thermal,simulation}$, solar irradiation on aperture area and absorber efficiency.

$$E_{thermal,simulation,non-selective} = G_{BN} \cdot A_{ap} \cdot \eta_{\text{absorber,non-selective}} \cdot \eta_{\text{collection,non-selective}} \qquad (5)$$

$$\eta_{\text{collection,non-selective}} = \frac{\dfrac{E_{thermal,simulation,non-selective}}{G_{BN} \cdot A_{ap}}}{\eta_{\text{absorber,non-selective}}} = \frac{\dfrac{1499\,\dfrac{GWh}{a}}{2636\,\dfrac{kWh}{m^2 a} \cdot 1497600\ m^2}}{0.850} = 0.447 \qquad (6)$$

Therefore the calculated thermal energy yield is equal to the simulated energy yield of 1499 GWh for the plant with non-selective receiver coating (base case).

The same thermal collection efficiency of 0.447 is now used for the static calculation of the thermal receiver output with selective coating (absorptance 95 %, emittance 40 %), assuming the thermal collection efficiency of the base case defines the general dynamic behavior of the system.

$$\eta_{\text{collection,selective}} \overset{\text{def}}{=} \eta_{\text{collection,non-selective}} = 0.447 \tag{7}$$

The absorber efficiency of the selective coating is adapted to the new coating parameters:

$$\eta_{\text{absorber,selective}} = \frac{\alpha_S \cdot Q - \epsilon \cdot \sigma \cdot \mathrm{T}^4}{Q} = \frac{0.95 \cdot 461{,}000 - 0.40 \cdot 5.67 \cdot 10^{-8} \cdot 973.15^4}{461{,}000} = 0.906 \tag{8}$$

The thermal energy yield calculated for the plant with selective coating with the static method results to 1598 GWh:

$$\begin{gathered} E_{thermal,simulation,selective} = G_{BN} \cdot A_{ap} \cdot \eta_{\text{absorber,selective}} \cdot \eta_{\text{collection,selective}} = \\ 2636 \frac{kWh}{m^2 a} \cdot 1497600 m^2 \cdot 0.906 \cdot 0.447 = 1598 \frac{GWh}{a} \end{gathered} \tag{9}$$

The energy yield calculated based on constant thermal collection efficiency is 1598 GWh. The thermal energy yield obtained by dynamic system simulation is 1539 GWh. The calculated yield is 3.7 % lower. If focus is put on the improvement due to new material developments, the deviation has to be put in relation to the performance improvement towards the base case. The simulated thermal energy yield is 2.7 % higher than for the system with the reference non-selective coating. The thermal energy yield based on the static approach improved by 6.6 %. This is more than two times higher improvement than determined by the more detailed dynamic approach. The improvement of the plant performance with selective coating was drastically overestimated using the static approach.

The reason for this again is the lower impact of improved functional parameters during hours in which parts of the heliostat field is defocused. Also changes in thermal efficiency during part load operation of the receiver are not taken into consideration in the static approach. This shows that not only material parameters, thermal and mechanical stability over time and costs have an impact on the success of a material development but also plant design and operation define the final impact of the development on thermal energy or electricity output as well as finally LCOE (Levelized Cost of Electricity) of a power plant.

CONCLUSION

A tool chain to evaluate the effect of key functional materials in solar tower power plants has been developed. Not only the behavior due to operation at off-design point at each minute of the year can be assessed, also degradation mechanisms can be taken into account over multiple consecutive years.

The thermal energy gain of the receiver over thirty years was shown. The LCOE of the reference system resulted to be 6.35 $Ct/kWh. If a selective coating of the same price is used, the LCOE could be reduced by 2.7 %. This was demonstrated by repeating the simulations with a generic selective coating of same absorptance, but an emittance of 40 %.

Furthermore an assessment on recoating intervals was conducted. The LCOE was calculated for different simulation scenarios. The interval of eight years turned out to be the ideal recoating interval that leads to the lowest LCOE.

Additionally an investigation on the benefit of dynamic simulation for the evaluation of functional materials was performed by comparing it to a method that uses static performance parameters. It showed that the dynamic behavior of a solar thermal power plant can change quite significantly, if another coating is used, mainly due to limitations in thermal load on the receiver and increased defocusing losses. The improvement of the plant performance with selective coating was two times higher using the static approach than using system simulation. To assess the impact of new coating developments in service, dynamic system simulation shows significant benefits.

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