Project Number: 686008

Project Acronym: RAISELIFE

Project title: Raising the Lifetime of Functional Materials for Concentrated Solar Power Technology

Final Technical Report

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Coordination: Dr. Florian Sutter (florian.sutter@dlr.de)

Contents

Glossary

AR	Anti-reflective
AS	Anti-soiling
BSII	BrightSource Industries (Israel) Ltd.
CASS	Copper Accelerated Salt Spray Test
CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
CNT	Carbon Nano Tube
CSP	Concentrated Solar Power
DEWA	Dubai Electricity and Water Authority
DFI	DECHEMA-Forschungsinstitut
DLR	Deutsches Zentrum für Luft - und Raumfahrt
EC	European Commission
EERA	European Energy Research Alliance
EIS	Electrochemical Impedance Spectroscopy
FEM	Finite Element Method
Fraunhofer	Fraunhofer-Gesellschaft, with its institutes Fraunhofer ISE and Fraunhofer IWM
HAZ	Heat Affected Zone
HiPIMS	High power impulse magnetron sputtering
HSA	High Solar Absorptance
HUJI	Hebrew University of Jerusalem
INTA	Instituto Nacional de Técnica Aeroespacial
IRR	Internal Rate of Return
ITO	Indium tin oxide
KPI	Key Performance Indicator
LCOE	Levelized Cost of Electricity
LFC	Linear Fresnel Collector
MASCIR	Moroccan Foundation for Advanced Science, Innovation and Research
MRL	Manufacturing Readiness Level
NSS	Neutral Salt Spray
O&M	Operation and Maintenance
PECVD	Plasma Enhanced Chemical Vapour Deposition
pp	percentage points
PROMES	Procedes, Materiaux et Energie Solaire
PSA	Plataforma Solar de Almería
PTC	Parabolic-Trough Collector
PVD	Physical Vapor Deposition
SAAF	Solar Accelerated Aging Facility at Odeillo (owned by PROMES)
SEDC	Solar Energy Development Center in Dimona, Israel
SOL	Laterizi Gambettola srl (SOLTIGUA)
SSRT	Slow Strain Rate Test
ST	Solar Tower
TRL	Technology Readiness Level
UCM	Universidad Complutense de Madrid
VAL	Vallourec

1. Summary for publication

Introduction

The European Renewable Energy Roadmap for 2020 establishes that 20% of final energy will be produced from renewable sources. With an increasing share of fluctuating wind and photovoltaic power generation, Concentrating Solar Power (CSP) technologies with thermal storage become more important due to the flexibility in dispatching power to the grid. In the Technology Roadmap published in 2014 by the International Energy Agency, the global electricity share of CSP systems is envisioned to reach 11% by 2050.

CSP has experienced a high learning rate in the past years, being able to provide renewable electricity at prices as low as 6 c€/kWh including storage for 6-15 hours. For these reasons the worldwide installed CSP capacity has increased by a factor of 10 in the past decade, reaching 5.5 GW_{el} today, and further growth being expected.

CSP plants of 1st generation were erected in 1984 and used parabolic-trough collectors with thermal oil as heat transfer fluid. The first commercial CSP plant with tower technology started up in 2007 with a saturated steam receiver and a 30-minute thermal storage system (PS-10 plant in Spain). The second generation of power-tower technology consisted of a molten-salt receiver and large capacity thermal storage system (GEMASOLAR plant in Spain and Crescent Dunes in USA, see also Figure 1).

The large initial investment for CSP plant construction does not come without risk: degradation of components and materials can hinder the plant's profitability. CSP plants are typically designed for a life span of 30 years, requiring the materials to withstand extreme thermal loads as well as harsh desert environment with high radiation and dust erosion levels.

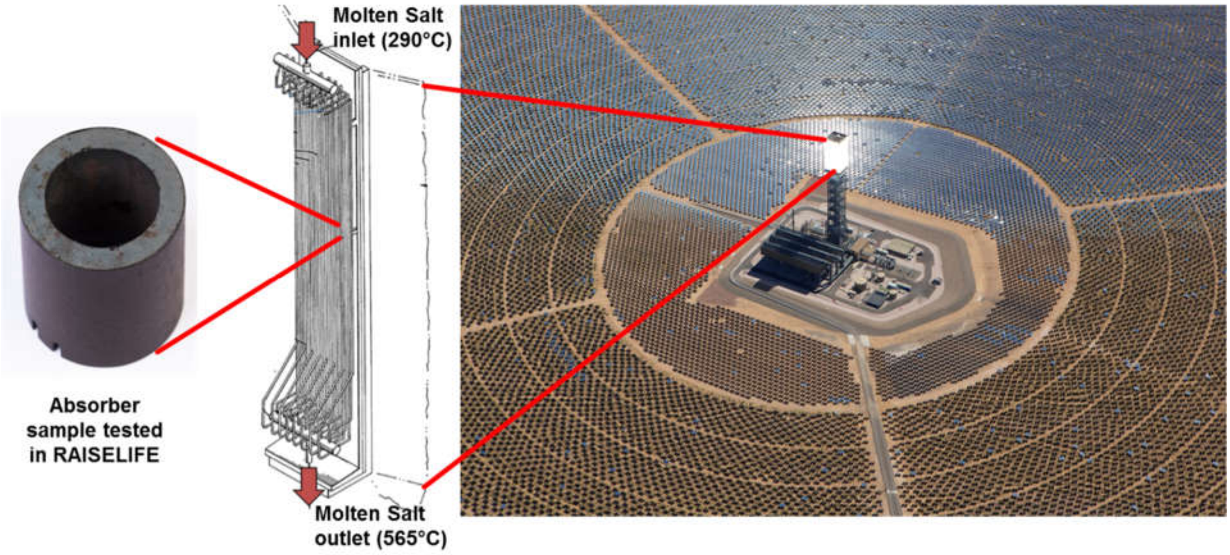


Figure 1 : Schematic of molten salt receiver panel in solar tower plants (only for illustration purposes; the image on the right shows the Ivanpah solar tower plant in California, which operates with steam instead of molten salt.)

RAISELIFE approach

The RAISELIFE project aimed at developing novel materials with extended lifetime and performance for parabolic trough and solar tower CSP plants. In addition, improved testing and qualification methods to simulate in-service conditions in different climates were developed.

The following materials were investigated in RAISELIFE: 1) protective and anti-soiling coatings for glass reflectors, 2) thin-glass composite reflectors for heliostats, 3) high-temperature secondary reflectors, 4) absorber coatings for tubular solar tower receivers, 5) absorber coatings for non-evacuated line-focus collectors, 6) abrasion resistant anti-reflective coatings for glass envelope tubes, 7) corrosion resistant high-temperature metals and coatings for molten salt.

The testing activities involved outdoor exposure and accelerated testing in climate chambers and under

concentrated solar radiation. Finally, a techno-economic analysis was conducted using system simulation tools. This had the aim to determine the economic benefit of the newly developed materials compared to the state of the art materials (see Figure 2).
The project brought together a broad consortium formed of industry partners, SMEs and research institutes of the CSP and material science sector with the final goal of increasing durability and performance of materials and in consequence reducing electricity generation costs.

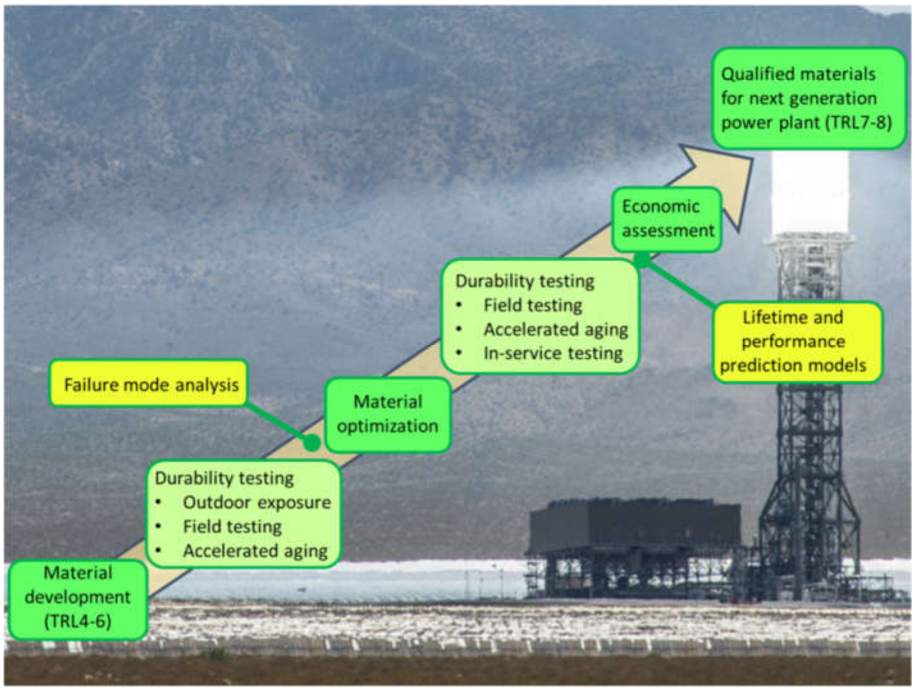


Figure 2 : Project approach

Main results

With regards to parabolic trough CSP plants, CIEMAT developed a novel absorber coating for non-evacuated line focusing systems based on cost-efficient sol-gel technology. The coating achieves **excellent optical performance and high durability** (α=95.5%, $\varepsilon_{250°C}$=13% deposited on stainless steel or $\varepsilon_{250°C}$=8.1% deposited on chromium plated stainless steel, stability >15 months in furnace at 400°C without degradation and negligible degradation after 14 months of field testing in a parabolic trough operating at 180°C at Soltigua in Italy). In addition, an improved anti-reflective (AR) coating has been developed by CIEMAT for evacuated line focusing systems, reaching 2.5 higher abrasion resistance compared to the state of the art. The novel AR-coating reaches a **solar transmittance of 97.2%** and has been deposited in the commercial receiver tube factory from Archimede Solar Energy in Italy on 15 glass tubes of 6 m length. The receiver tubes were installed and tested during 12 months in the Linear Fresnel collector from Soltigua in Italy at a temperature of 180°C. Soltigua cleaned the samples twice per month using pressurized water for all samples followed by tissue cleaning for only half of the samples to understand the abrasion process. It was found that the transmittance of all samples stayed above 95.1% after exposure. There was no clear evidence that the more efficient pressurized water and tissue cleaning method induces stronger degradation compared to only pressurized water cleaning.

With regards to solar tower CSP plants, four different types of novel absorber coatings for temperatures up to 750°C have been developed. Durability testing of those coatings was carried out in two sets of tests under high solar flux (up to 700 kW/m²) to mimic operation conditions and in several climatic chambers to mimic environmental corrosion and erosion during night-time or plant shutdown. Figure 3 shows one of the two employed on-sun testing facilities. The BSII and INTA-BSII coatings tested were identified as very promising: **they showed similar optical performance as the state of the art Pyromark 2500 absorber coating but significantly higher durability.** The expected lifetime of the BSII coating on T91 ferritic steel (for steam application) is 6-8 years, requiring local repair works due to oxidation of the

substrate steel. On the other hand, the lifetime of the BSII coating applied on nickel-base alloy Inconel 617 substrate (for molten salt application) is expected to endure even for 15 years, according to the lifetime model developed in RAISELIFE. As result of the high durability and excellent optical performance of **97% of solar absorptance**, BSII decided to **employ the receiver coating tested in RAISELIFE within the 100MW commercial solar tower project DEWA in Dubai**.
In addition, O&M procedures and coating application were simplified. On the one hand, similar durability of solar and furnace cured coating was demonstrated in solar cycling tests in the dish concentrator on Inconel 617 opening the possibility for **direct solar on-tower recoating** instead of costly ground curing of the freshly coated panels in large furnaces. On the other hand, BSII developed and **automatic coating machine prototype**, capable to coat 2 x 2m² receiver panels with low coating thickness variances.

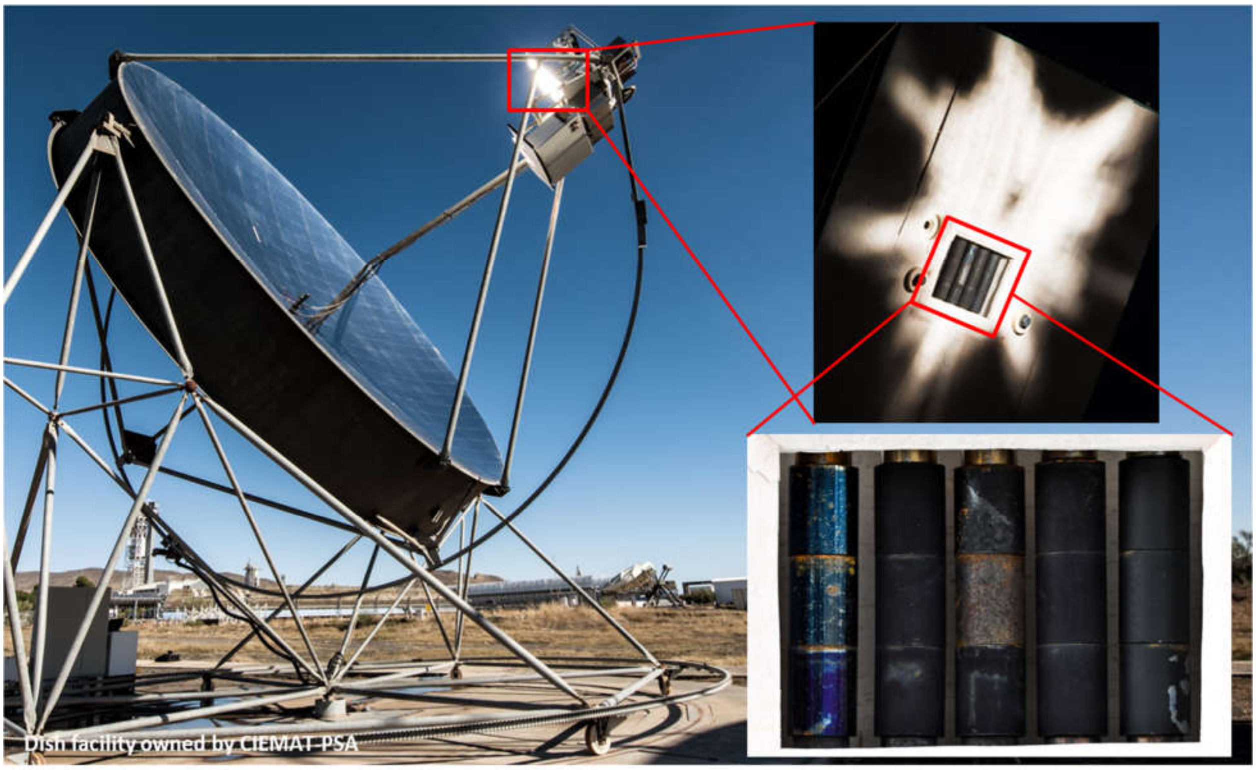


Figure 3: Accelerated aging testing of different absorber coatings in the dish concentrator test bench at Plataforma Solar de Almería (PSA). A similar facility (SAAF) is located at PROMES in France.

Protective coatings to prevent corrosive attack from the molten salt on the inner side of the metallic tube substrates have been developed. The coated samples showed only **negligible mass losses during furnace testing in solar salt at 580°C for 10,000 hours**, opening the pathway to use low-alloyed steels in combination with coatings for the molten salt storage and piping systems, which will allow for further cost reductions compared to the use of expensive nickel base alloys. The corrosion rate of different uncoated substrate materials has been evaluated as reference: for the ferritic steels, Vallourec's VM12 performed significantly better that T91 (corrosion rate of 59µm/year compared to 169µm/year in solar salt at 580°C). Low corrosion rates were measured on nickel base alloy Inconel617 (15µm/year in solar salt at 580°C).

All CSP plants make use of silvered-glass mirrors to focus the solar radiation towards the receiver (see Figure 4). Traditional glass mirrors have a thickness of 4 mm and the silver layer is protected by a thin copper film and 3 protective paint lacquers. Within RAISELIFE, 4 types of mirror systems containing only copper + 2 protective lacquers have been developed and tested in an extensive outdoor exposure campaign at 11 sites, as well as in a set of accelerated climate chamber tests. Three of the tested mirror types proofed to be suited for dry desert sites of low corrosivity, allowing to **reduce mirror cost below 12 €/m².** In addition, an environmental friendly lead-free coating was tested and showed even lower degradation rates compared to the other low-cost coatings. Five types of anti-soiling coatings to reduce mirror soiling and therefore the cleaning cost were tested, showing that a cleanliness gain up to 1.5 percentage points (pp) is possible by using coatings. Furthermore, a thin-glass heliostat prototype was built and tested in Israel. The composite backing structure proved to provide stability against high wind loads and showed cost reduction potential up to 30% compared to previous BSII design.

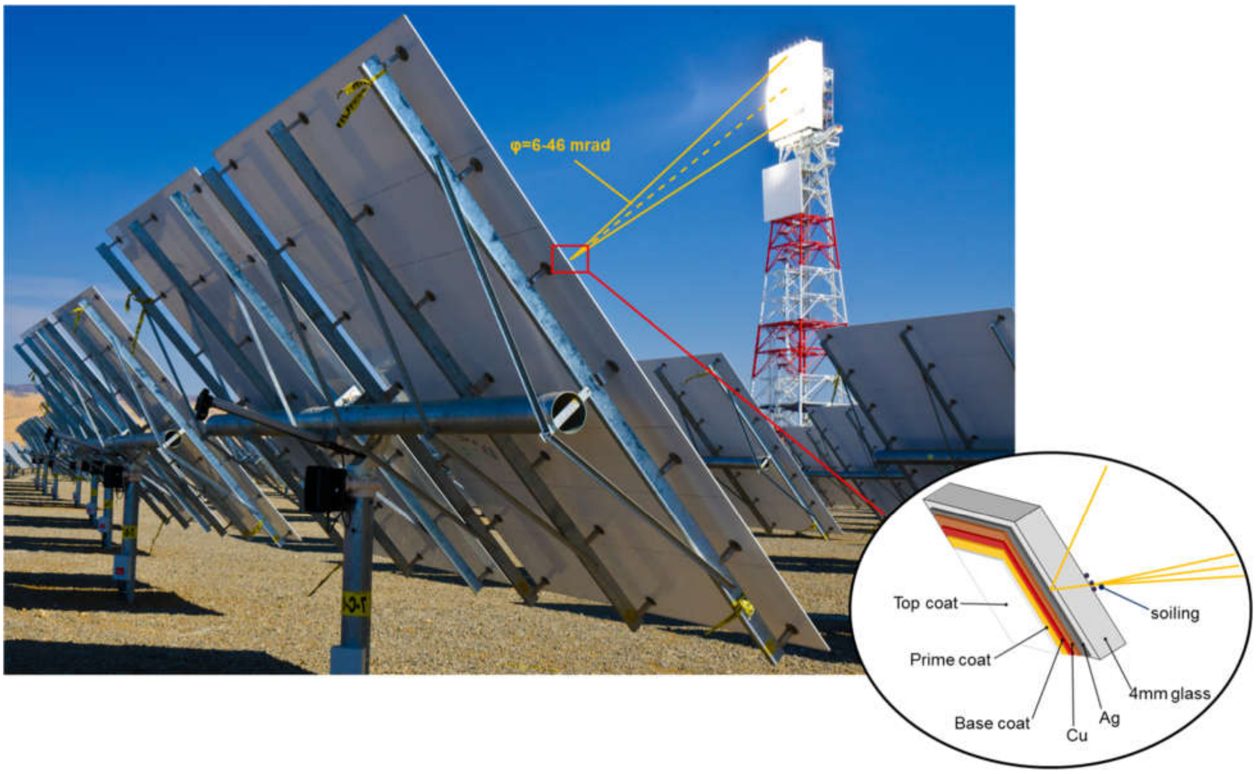


Figure 4 : Schematic of silvered-glass mirror mounted on heliostats to reflect solar radiation towards the receiver.

2. Overview of results

2.1 Solar Reflectors

Corrosion of state-of-the-art silvered-glass mirrors is mainly determined by the applied protective backside coating system. Two commercial and five novel mirror coatings (see Table 1) were analyzed within the project in 11 outdoor environments and by accelerated aging. The aggressiveness of the outdoor exposure sites was determined, categorizing them into corrosivity (C1-C5 and CX for extreme corrosion, according to ISO9223[1]) and erosivity classes (E1-E3, according to the methodology developed within the project[2]). **Negligible degradation is measured for all mirror types (except RFA5, which failed) in low corrosive, desert CSP-site conditions (corrosivity C2).** Under these conditions, usage of 2-paint layered mirror coatings RLA2, RLA3, RLA4, RLB3 is thus advisable to save CAPEX. Higher degradation rates were determined for sites of corrosivity C4. The 3-paint layered commercial coating showed to be the best choice for such kind of environment.

Table 1 : Mirror coating systems tested in RAISELIFE (the reflectance ρ is expressed in sun-conic solar-weighted specular reflectance at incidence 10° and acceptance angle of 12.5mrad).

Material code	RLA1	RLA2	RLA3	RLA4	RLA5	RLB1	RLB3
Number of layers	3	2	2	2	2	2	2
Characteristics	Commercial	Low-cost	Lead-free	Low-cost	Powder coating	Commer-cial	Low-cost
ρ(SW, 10°, 4.7mrad, ϕ)	95.1	95.1	95.3	95.4	94.6	95.6	95.6
After 3 years (RLA) / 2 years (RLB) in C2-E1, ρ(SW, 10°, 4.7mrad, ϕ)	95.1	95.0	95.3	95.3	Fail	95.6	95.5
After 3 years (RLA) / 2 years (RLB) in C4-E1, ρ(SW, 10°, 4.7mrad, ϕ)	94.9	94.8	95.0	94.9	Fail	95.4	95.4

Accelerated aging methodologies were improved and **two guidelines** were developed: one to predict the corrosion in different exposure sites and one to compare different reflector materials among each other, ranking their expected durability.

The first guideline is based on correlating measured corroded area between outdoor corrosivity classes and the accelerated CASS test, obtaining a service lifetime prediction. As seen in Figure 5 left the predicted lifetime of the novel low-cost 2-paint mirror coatings is as high as for the commercial 3-paint coatings in a C2 site. For C3 and C4 sites however, the commercial 3-paint coatings proved to perform better. Thus, **usage of low-cost 2-paint mirror coatings is only advisable for corrosivity sites of C2.**

The second guideline is based on the Spanish UNE 206016 standard[3], which was published in 2018 under leadership of the RAISELIFE partners DLR and CIEMAT. The novel RAISELIFE guideline includes updated recommendations for testing times to establish meaningful material comparisons[4]. For example as shown in Figure 5 right, 480h of CASS test reproduces the ranking of material durability determined during outdoor exposure during 2 years in Almería fairly well. Rank 1 means that the material shows the lowest number of detected corrosion spots of all 5 tested mirror types, while rank 5 means that the highest number of spots was detected.

[1] ISO9223 (2012): Corrosion of metals and alloys - Corrosivity of atmospheres - Classification, determination and estimation

[2] F. Wiesinger et. al (2020): Sandstorm Erosion on Solar Reflectors: Highly Realistic Modeling of Artificial Aging Tests Based on Advanced Site Assessment, accepted manuscript in Applied Energy, to be published in March 2020.

[3] UNE 206016 (2018): Reflector panels for concentrating solar technologies.

[4] Sutter et. al (2019): Acceptance criteria for accelerated aging testing of silvered-glass mirrors for concentrated solar power technologies. Solar Energy Materials and Solar Cells Volume 193, May 2019, Pages 361-371. https://doi.org/10.1016/j.solmat.2019.01.008

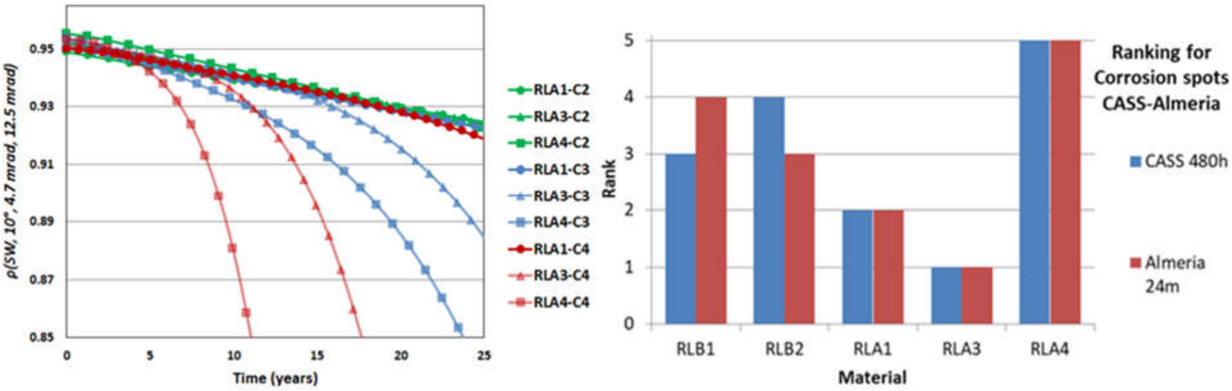
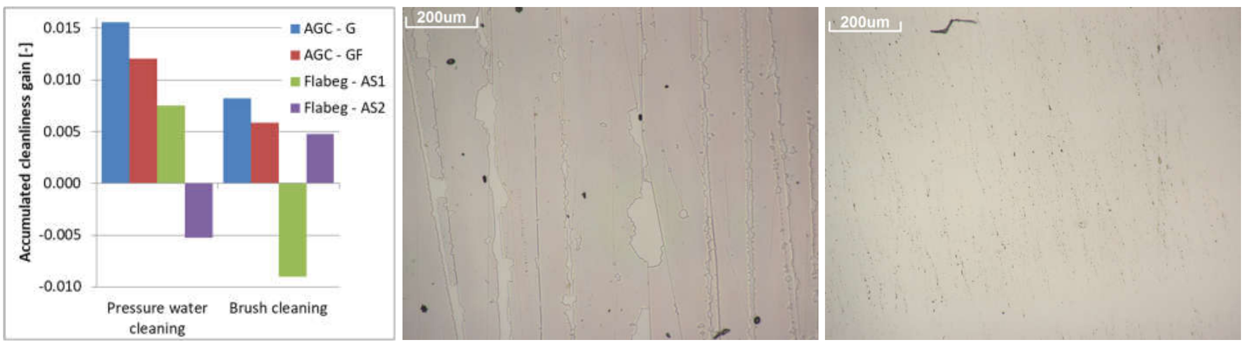


Figure 5 : Left) Predicted reflectance drop of 3 materials during exposure at exposure sites of corrosivity C2, C3, C4. Right) Durability ranking for outdoor and CASS test of 5 materials.

In addition to protective mirror coatings, anti-soiling coatings deposited on the front glass of the reflector were tested. These coatings have the potential to tackle certain issues with the solar field performance: avoid strong soiling, maintain higher reflectance, less frequent and easier cleaning in connection with lower water consumption. The ability of the coatings to prevent soiling and facilitate cleaning as well as to maintain these characteristics over a long time was investigated for 5 novel anti-soiling coatings. One experimental liquid coating was discarded after a short exposure period and is not included in the final evaluation graphic in Figure 6 a. Through outdoor and accelerated testing, it was possible to quantify the advantage of the coatings, that is, their cleanliness gain compared to uncoated reference mirrors. Depending on the type of coating and the cleaning technique applied, **a cleanliness gain of over 1.5 pp was determined** (see Figure 6 a). Degradation due to cleaning was detected for certain coatings (see Figure 6 b for AS1) and due to residues on the coating surface (Figure 6 c for AS2), lowering the reflectance and compromising the anti-soiling effect, thus discarding them as candidate materials for commercial deployment. Mechanical damages were identified as the main degradation mechanism for the coatings during the outdoor exposure tests. This is why the focus was on mechanical tests in the laboratory. Tests and parameters have been selected to properly reproduce damages detected outdoors. The laboratory tests confirmed the low mechanical resistance of AS1 and the liquid coating. HUJI developed three novel, hydrophobic and transparent anti-soiling coatings and applied the successfully on commercial mirrors. The samples showed excellent anti-soiling properties in laboratory tests. However, insufficient performance was detected during outdoor exposure testing, consequently further optimization of HUJI's coatings is required.



a) b) c)

Figure 6 : a) Accumulated cleanliness gain of different materials and cleaning techniques after 22 months of exposure at for AS1 & AS2 and 14 months of exposure for G & GF at the PSA, b) Damaged AS1 coating after brush cleaning, c) Residues on AS2.

Finally, a **novel composite heliostat was designed and installed** at the SEDC pilot site in Israel in autumn 2018 by BSII (see Figure 7). Due to the high stiffness and low weight of the composite sandwich material, the size of the heliostat was increased from traditional BSII design of 25.7m² to **40m²**, maintaining its resistance to wind loads >45m/s. The increased size has a great economic impact on all works related to the solar field, such as dirt moving, foundations, roads, etc. The entire heliostat was assembled in one single afternoon and using very simple tools. The utilization of the composite sandwich also allowed the selection of (ultra-) thin glass mirrors instead of conventional self-sustaining 4 mm glass reflectors, obtaining about **0.5pp higher reflectance** due to reduced absorptance losses in the glass. Four types of thin glass mirrors (of 1 mm thickness), with reduced back side coating systems, and one experimental ultra-thin glass (0.2 mm) mirror were glued to the composite material and tested as candidate reflective surface for the heliostat. The ultra-thin mirror was discarded in an early project stage, mainly because of high manufacturing costs and low mechanical protection (e.g. by small impacts). All sandwich reflectors showed **superior resistance to corrosion** compared to traditional reflector materials because the backing composite material acts as an excellent diffusion barrier protecting the reflective silver layer.

Laser scanning of the prototype composite heliostat has been performed at SEDC BSII pilot site, as well as in laboratory tests on small 50 x 50 cm^2 samples by Fraunhofer. Both, at laboratory tests as well as on the large heliostat, it was recognized that: (1) the impact of environmental temperature on the composite material creates an optical deformation (unlike the negligent impact for 4mm glass mirror) (see example in Figure 7b); (2) The large surface of the thin-glass composite panels and the supporting structure suffer deformations due to the gravitational force at the various angular positions of the heliostat (see Figure 7c). Altogether, the impact on the overall optical efficiency loss can be in the order of ~1 %, which can be minimized in future designs. Nevertheless, the decrease in performance is largely outweighed by the advantages of the composite heliostat.

The potential gain is in the order of **30% cost reduction**, mainly due to the allowable larger reflective surface. The thin-glass composite heliostat is an attractive improvement – surpassing the original US DOE road map goal for solar field reflectors **from \$75/m² to about \$50/m² heliostat cost**.

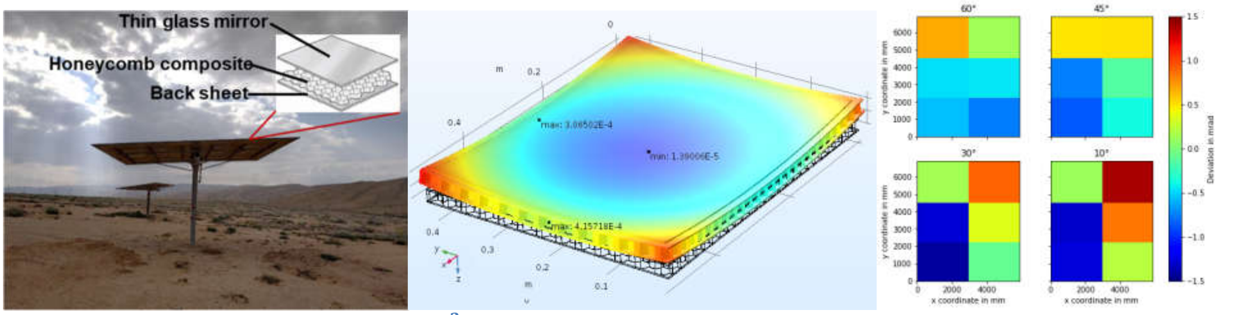


Figure 7 : a) Heliostat of size 6.9 x 5.9 m^2 erected in Israel, including sandwich reflector (composite + thin glass mirror), b) Deformation of sandwich due to temperature changes in lab experiments, c) Slope deviation of heliostat facets due to gravitational loads for elevations angles 10, 20, 45 and 60°.

2.2 Secondary Reflectors

Secondary reflectors used in solar towers (ST) and Linear Fresnel Collectors (LFC) to redirect solar beams reflected by primary concentrators into the receiver (Figure 8 a). High temperature materials able to resist high radiation levels are mandatory for this type of reflectors, especially if water cooling systems are avoided for reasons of cost savings and to lower the risk of plant shut down due to cooling system failure. The goal in this WP was to develop a secondary reflector which is able to survive under real conditions in a ST without a cooling system.

The first step consisted of analyzing the thermal field of the secondary, through a thermal 3D FEM model (Figure 8 b). Different geometric and optical variations with several load cases were analyzed. The results show that the backside of the reflector must be black (emissivity: 0.95) to dissipate the heat and the reflectance should >0.95 to assure that the **temperature limit of 400°C** is not exceeded. Even then a minimal convective cooling is necessary. The needed heat transfer coefficient for sufficient cooling is about 10 W/m^2K (ambient temperature: 22 °C), which could be reached by natural convection. One weakness of this model is that the convective losses are modelled using a homogenous heat transfer coefficient. In reality the air could be heated up by the absorber (natural convection), which would result in a reduced cooling effect. Windy situations could lead not only to higher heat transfer coefficients, also lower or zero heat transfer could occur in some regions due to recirculation zones. Furthermore, a lower reflectance (dust ore aged reflective coating) would lead to much higher temperatures, exceeding the set limit of 400 °C.

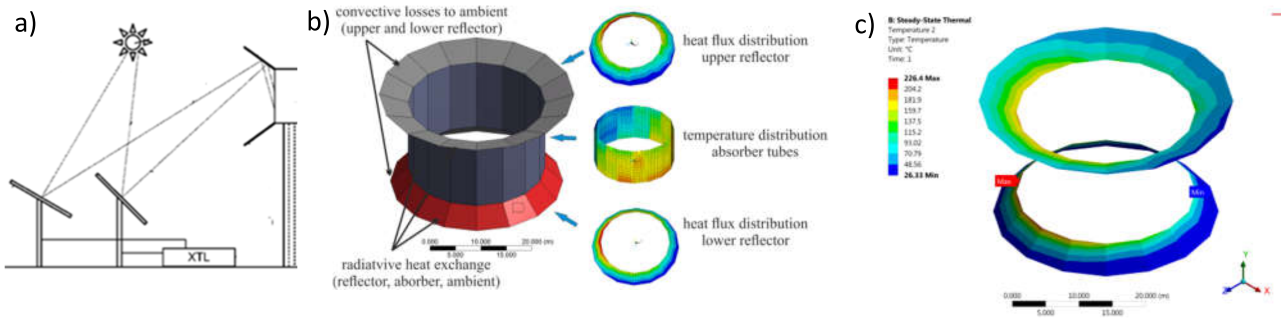


Figure 8 . a) Principal scheme of a secondary reflector, b) thermal model , c) thermal field in °C

Fraunhofer ISE investigated a secondary reflector based on **highly polished steel substrates and a silver-based sputtered thin film coating**[5]. A schematic of the mirrors developed by Fraunhofer ISE is shown in Figure 9 left. The top barrier layer consisted only of a sputtered layer and both adhesion and bottom barrier layers were sputtered metal.

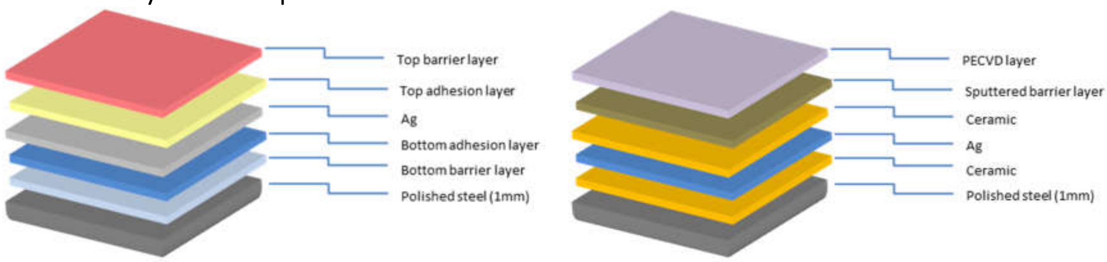


Figure 9 : Left) Schematic of the 'first' generation silver-based sputter coated polished steel, Right) 'second generation' silver-based sputter coated polished steel with a PECVD top barrier layer.

This first generation of secondary materials was tested at CIEMAT-PSA. The durability test campaign typically applied to primary mirrors was adapted taking into consideration the operating conditions of high radiation. The mirrors of first generation (Figure 9 left) presented an initial average solar hemispherical reflectance of $\boldsymbol{\rho_{s,h}}$**=0.913**. Figure 10 left shows the evolution of $\rho_{s,h}$ in the solar furnace test[6] (10 days of operation at 350 kW/m^2, which involved 36 h at 400°C and around 20 temperature cycles from 50°C to 400°C), where a continuous deterioration of the reflectance can be clearly seen, reaching a value of $\Delta\rho_{s,h}$=0.055 after testing (see Figure 11 left). In addition, Figure 10 right depicts the behaviour of the samples during the three constant temperature tests. As can be seen, the 1st generation samples did not suffer any degradation at 350 °C, while significant and very high loss of reflectance was noticed in the tests at 400 and 450°C, respectively. The test at 450°C was interrupted after 250 h due to the high reflectance drop and the total **"bluing" of the samples** (see Figure 11 middle). With respect to the rest of the accelerated aging tests performed, **no reflectance decrease** was noticed, except for the thermal cycling (250 cycles from ambient to 400°C), with a drop of $\Delta\rho_{s,h}$=0.013.

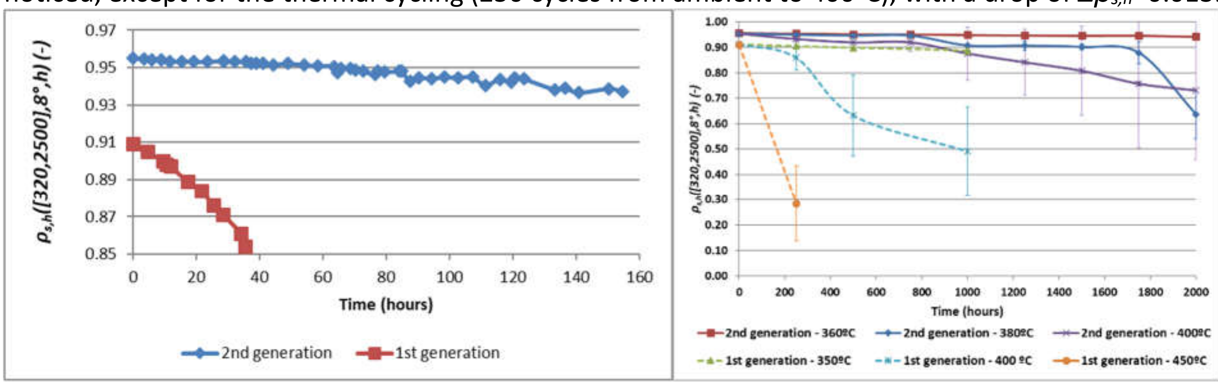


Figure 10 : Solar hemispherical reflectance of the first and improved samples for the solar furnace test (left) and for the constant temperature tests (right).

[5] S. Gledhill et. al: HiPIMS and DC Magnetron Sputter-Coated Silver Films for High-Temperature Durable Reflectors. Coatings 2019, 9(10), 593.

[6] D. Arguelles-Arizcun et. al: New set-up to test secondary concentrators under real solar radiation with high concentration. AIP Conference Proceedings 2019, 2126, 160001.

In the solar furnace, localized increase in absorption leads to a local temperature jump which degrades the reflective layer (see "hot-spot" in Figure 11 left). Auger Electron Spectroscopy revealed that **the bottom metal adhesion and barrier layer had diffused through the silver layer** (see Figure 11 right). A range of materials were subsequently scanned and tested. Finally, a ceramic layer was used to replace the metal system for the 2nd generation of samples.

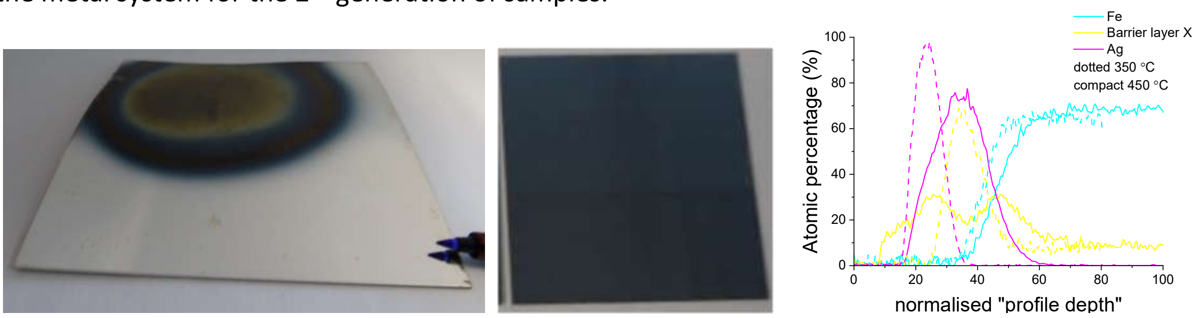


Figure 11 : Photographs of the 1st generation tested in the solar furnace at 400ºC for 36 h (left) and in the muffle furnace at 450°C for 250 h (middle). Auger Electron Spectroscopy revealing the diffusion of the barrier layer material X into the silver for the sample exposed to 450°C in comparison to no diffusion seen at 350°C (right).

The 'second generation mirror' stack (see Figure 9 right) thus incorporated the **ceramic bottom barrier and adhesion layer system which does not exhibit diffusion**. It also had a ceramic top adhesion layer to allow for maximal reflectance and a PECVD layer (which had shown improved performance in humidity-based in experiments at the Fraunhofer ISE tests). The improved samples (which presented higher initial reflectance of $\boldsymbol{\rho_{s,h}}$**=0.955**) were tested in the constant temperature tests at 360, 380 and 400°C for 2000 h and in the temperature cycling test from ambient to 380°C for 250 cycles. With respect to the solar furnace test, the solar flux was kept at 350 kW/m^2 (with an air cooling system). The test was performed during 46 days (around 3 natural months), and in total, the sample was exposed to 380°C during 155 h and around 388 temperature cycles from 50°C to 380°C were conducted, simulating start-up/shut-down of the power plant operation as well as transients by clouds. Finally, the second generation samples were submitted to a more extended accelerated aging campaign, to assess the behaviour under a wide range of ambient conditions (see testing conditions in Table 2). Results from the solar furnace test are shown in Figure 10 left, where a significant improvement of the behaviour was noticed with respect to the 1st generation samples, with a final reflectance of $\boldsymbol{\rho_{s,h}}$**=0.937**. Regarding the constant temperature tests, results are depicted in Figure 10 right. In this case, no degradation was perceived in the samples tested at 360°C, while a remarkable degradation was noticed at the two higher temperatures (at 380 and 400°C) in the last phases of the tests. Table 2 presents a summary of the solar hemispherical reflectance drops. As can be seen, the degradation is negligible for the thermal cycles, condensation and washability tests, slight for the Taber, sand storm, CASS, UV+humidity tests (with reflectance decays from 0.014 to 0.026), and high for the NSS test (with a reflectance drop of $\Delta\rho_{s,h}$=0.194).

Table 2 : Solar hemispherical reflectance drop for the improved mirrors in the accelerated aging tests.

	Thermal cycles	**Conden-sation**	**UV+ humidity**	**Damp heat**	**NSS**	**CASS**	**Sand storm**	**Taber**	**Washa-bility**
Conditions	30 to 380ºC	ISO 6270	ISO 16474	IEC 62108	ISO 9227	ISO 9227	70 g, 20 m/s	ISO 9211	ISO 11998
Duration	250 c	480 h	1000 h	550 h	480 h	120 h	3 c	200 c	200 c
$\Delta\rho_{s,h}$	-0.004	0.000	-0.024	-0.026	-0.194	-0.021	-0.016	-0.014	-0.001

Finally, the costs of the secondary reflector were estimated based on a conceptual design of the reflector and its support structure (Figure 12). The basic design concept foresees **trapezoidal bended reflective coated sheet metal**. The geometric design of these reflector elements gives mechanical stability and an improved cooling by convection due to the channel like geometry. The reflector segments are mounted on a frame support structure. The modular approach supports the installation (unit by unit) and service (replacements). The costs of the secondary reflector were estimated based on specific manufacturing numbers for steel frame (2 €/Kg) and the sheet metal for the reflector segments (4 €/Kg), leading to costs of about **460'000€**.

(a) (b) (b)

Figure 12 :Design, (a) reflector segment, (b) reflector unit (upper reflector), (c) receiver with secondary.

To conclude, it can be highlighted that the material development and testing campaign gave clear insights into how a better and more robust silver-based sputter film system on polished steel should be further developed. Some specific remarks are as follow:

- An additional barrier layer in the form of a PECVD layer improves the stability in the damp-heat tests as a function of increasing film thickness (when combined with a suitable stable sputtered system). The thickness of the PECVD has a maximum viable value due to thermal-induced stresses which cause film cracking.
- The ceramic adhesion layer of the 2nd generation mirrors achieved a higher reflectance of $\rho_{s,h}$=0.955.
- The ceramic bottom layer used in the 'second generation' mirrors did not inter-diffuse into the silver layer. The 'second generation' reflectors were much more durable than the 1st generation mirrors in the solar furnace, presenting a reflectance value of $\rho_{s,h}$=0.937 after the test.
- The 'second generation' mirrors failed the tape adhesion tests due to a less effective adhesion layer. This meant the mirrors performed poorly in the damp heat tests. The top barrier layer blisters and peels off, due to de-cohesion; causing increased light scattering and subsequent film degradation. This lowed the long-time durability at constant temperature of 380°C.
- Since the 'second generation' mirrors were delivered further research and development to the sputter system has been carried out. Using both metal and ceramic sequenced layers a good adhesion has been achieved which has shown to be stable for >1500 h at 450°C with a stable reflectance of $\rho_{s,h}$=0.920 maintained from start to finish of testing.
- An active cooling of the reflector segments could therefore make the design more robust. In this case the reflector segments could be designed as trapezoidal closed channels in which air is blown. The support frame existing of hollow profiles could be used for distributing the cooling air.

2.3 Solar receivers

2.3.1 Solar receivers for solar tower

Four novel absorber coatings for solar towers have been developed within the RAISELIFE project: a ceramic paint (BSII), an aluminide primer (INTA), a PVD selective coating (Fraunhofer) and a multi-metallic diffusion coating (DFI). The coatings were tested under a large set of accelerated aging tests [7,8]. Based on the detected degradation, the formulation of each coating was improved and a second generation was developed. One example of the conducted optimization is the combination of the selective coating with the aluminide primer with the aim to suppress diffusion of coating elements into the substrate (coating E INTA+Fraunhofer). Figure 13 shows the initial optical properties and the degradation rate measured for the second generation of coatings as applied on Inconel 617 substrate under accelerated aging compared to the reference coating Pyromark2500. It can be seen that the BSII coatings achieves similar optical performance than Pyromark2500 while the measured degradation is considerably lower. The developed lifetime model predicts that the **solar absorptance of the BSII coating will remain above 95% for about 7 years on T91 and about 15 years on Inconel 617**. As a result of the testing activities carried out in the project, **BSII decided to employ the novel absorber coating in their next commercial solar tower plant in Dubai.**

[7] S. Caron et. al: Accelerated ageing of solar receiver coatings: Experimental results for T91 and VM12 steel substrates. AIP Conference Proceedings 2033, 230002 (2018); doi: 10.1063/1.5067230

[8] R. Reoyo-Prats et. al: Accelerated aging of absorber coatings for CSP receivers under real high solar flux – Evolution of their optical properties. Solar Energy Materials and Solar Cells 193 (2019) 92–100

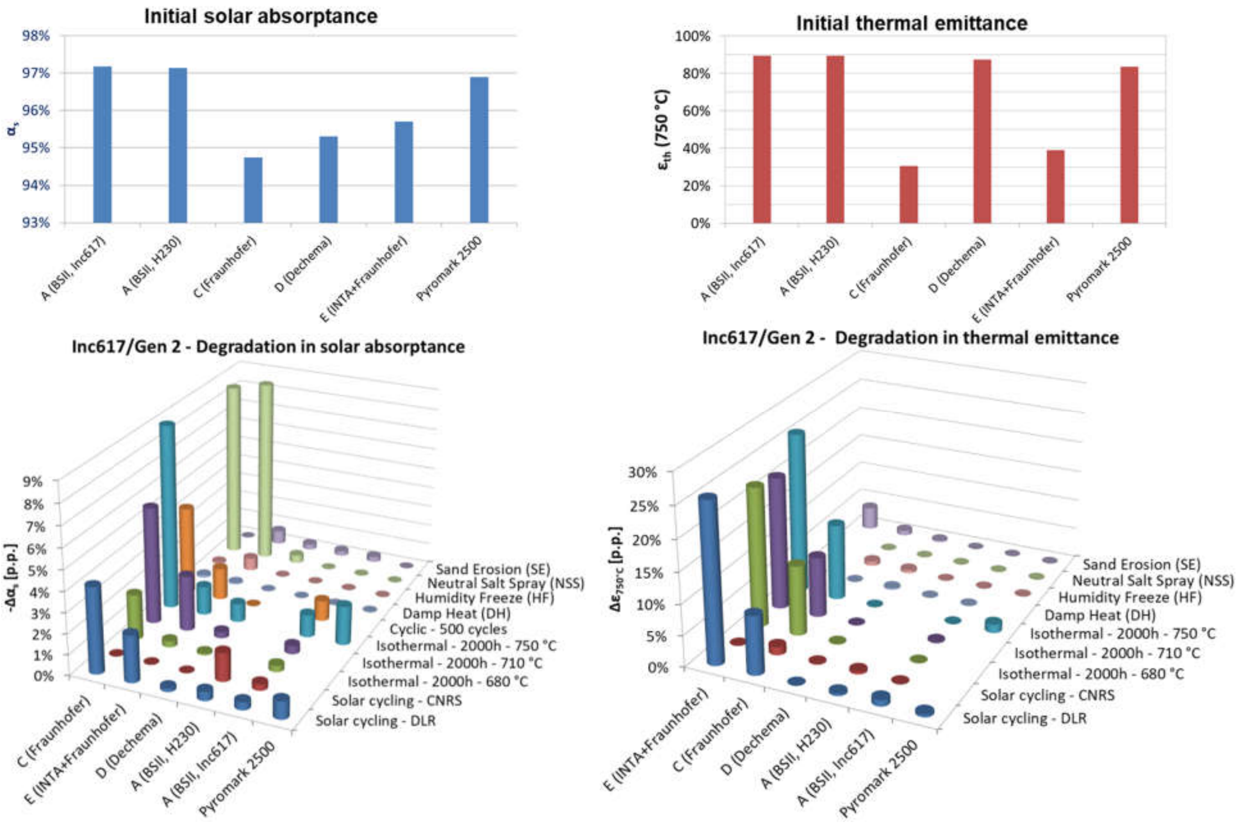


Figure 13 : Left) Initial (top) and measured decrease (bottom) in solar absorptance of the different coatings after the accelerated aging tests applied. Right) Initial (top) and increase (bottom) in thermal emittance after accelerated aging. The values of the reference state of the art coating Pyromark2500 are based on own measurements and literature data.

The absorber coating employed by BSII in Ivanpah already showed good results: after 7 years of operation (+ 2 years construction) no major failures occurred; only local repair works were conducted and rarely entire panels were recoated (see Figure 14 left). On-tower recoating is desirable to reduce the O&M cost but also challenging. Cleaning and surface preparation, painting, and the complicated solar curing profile need to be all conducted at tower heights of more than 200 meters. In RAISELIFE it was demonstrated for the first time, that **solar curing is possible proving similar optical parameters and durability of solar and furnace cured coatings** in solar dish cycling tests. In addition, an automatic coating machine was developed to coat prototype panels up to 2x2m² (see Figure 14 right). The **automatic machine proofed to achieve coating thickness tolerances of only 5 µm** (compared to 20µm for manual painting), meaning that coating "weak points" will be reduced and even higher durability can be expected from automatically coated receiver panels.

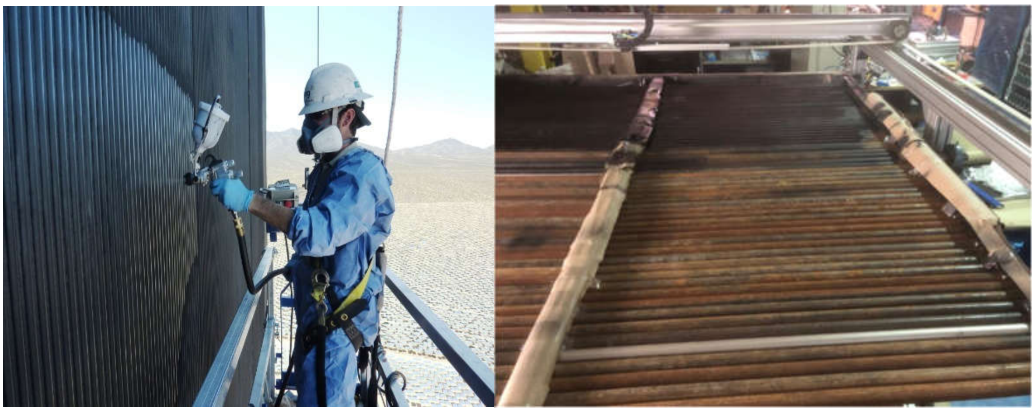


Figure 14 : left) recoating of receiver panel in Ivanpah power plant by BrightSource, USA, right) Mid-sized automatic coating machine while coating a test panel

2.3.2 Solar receivers for line focusing systems

Selective absorber for non-evacuated line focusing absorber tubes

Selective absorber coatings developed by CIEMAT have been improved during the RAISELIFE project, adding an additional chromium infrared reflective layer to reduce thermal emittance. **Solar absorptance remains unchanged at 0.955 but thermal emittance has been reduced from 0.133 to 0.087** regarding absorber prepared directly on stainless steel substrate (see Table 3 and Figure 15 left). Thermal durability has been tested at different temperatures and absorber has maintained optical properties at 400°C in air during 15 months of furnace testing. **Only negligible degradation has been detected after 14 months of field testing at 180°C by Soltigua.** First signs of degradation are seen at 450°C (see Table 3).

Table 3 : Optical properties of chromium coated stainless steel selective absorber as prepared, after 15 months at 400ºC and after 12 months at 450°C.

	Initial	*After 15 months at 400°C*	*After 12 months at 450°C*
Solar absorptance	0.954	0.956	0.932
Thermal emittance (250°C)	0.087	0.091	0.137

Antireflective (AR) coating for evacuated line focusing absorber tubes

Antireflective coating has been improved during RAISELIFE project:

- Solar transmittance has been increased from 0.965 to 0.972
- Mechanical resistance according TABER abrasion test has been improved and number of strokes required to remove completely the coating has been increased from 40 to 100 (see Figure 15 right).
- Transmittance stayed between τ =95.1% - 96.1% after 12 months of field testing at Soltigua at 180°C, including 2 cleaning cycles per month.

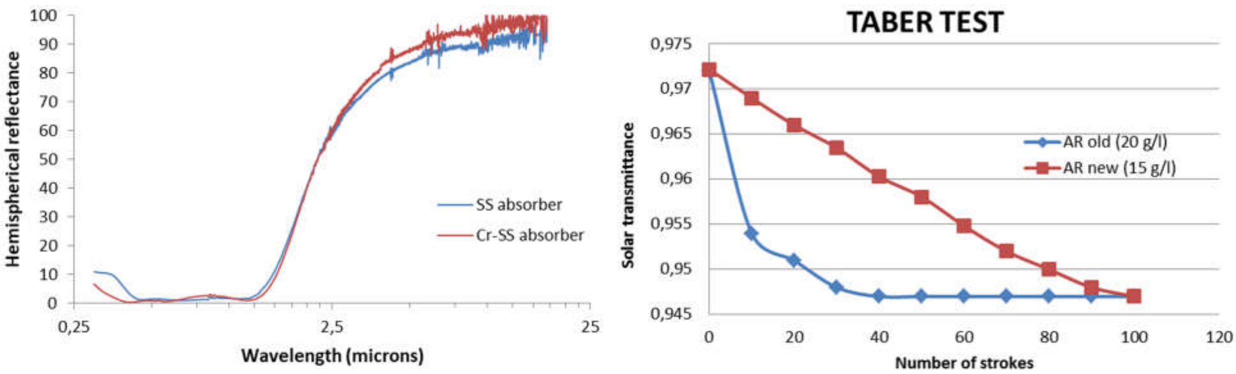


Figure 15: Left) Hemispherical reflectance, in solar and IR spectral range, of stainless steel and chromium coated stainless steel absorbers developed during RAISELIFE project. Right) Solar transmittance vs. number of strokes in the Taber abrasion test of samples prepared with new precursor solution (15g/l of Triton X-100) and old solution (20g/l).

2.4 Coatings for molten salts

With the aim to develop cost effective materials for molten salt environments, corrosion resistant coatings for ferritic steels have been developed. Vallourec provided material as flat coupons (20x10x3 mm) of T91 and VM12-SHC (also called VM12) to be coated and used for the lab tests. T91 and VM12 are respectively 9% and 11% chromium steels currently used in conventional boilers at around 560°C to 600°C.

The testing protocol for salt exposure tests within RAISELIFE has been based on *ISO 17245*[9]. Tests were performed with at least three test pieces of each material with exposure times up to 10,000 hours.

INTA developed **three aluminide coatings** named INTA 1-3 (see [10] or Deliverable 4.1). Because INTA3 showed the highest mass gains after 1,000 h at 560°C and 580°C and INTA2 evidenced interdiffusion between coating and substrate, INTA1 (Figure 16) was selected as the best coating to continue for the long-exposure tests (see Figure 18 for the results).

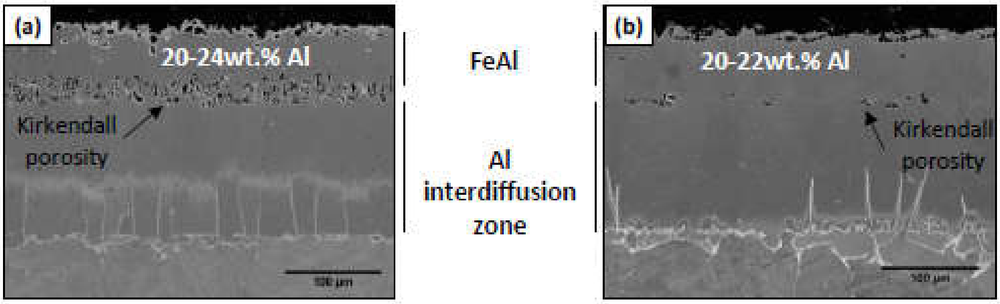


Figure 16 : INTA 1 coating on (a) P91 and (b) VM12-SHC

DECHEMA developed two diffusion coatings to improve the corrosion resistance of the steel substrates (T91 and VM12) during molten salt corrosion tests[11]. Both coatings were deposited via the industrially well-established powder pack cementation method. The first coating (DFI1) was manufactured by the **co-deposition of Cr and Mn**, which resulted in the formation of Cr-Mn carbide at the surface as well as a Mn-diffusion zone (same coating, which was initially tested for the outside of the tube but discarded due to its low solar absorptance). However, DFI1 coating formed non-protective iron oxides due to the outward diffusion of Fe and consequentially a high mass loss during short term exposure at 560°C, as further explained in Deliverable 4.1. Hence DFI developed a second coating (DFI2), which was manufactured by the sole **deposition of Cr** and resulted in the formation of a homogenous $Cr_{23}C_6$ layer as shown in Figure 17. As stated in Deliverable 4.1, this coating showed a higher corrosion resistance in molten salt exposure tests compared to DFI1 and thus was selected for the long-exposure tests and the subsequent microstructural characterization.

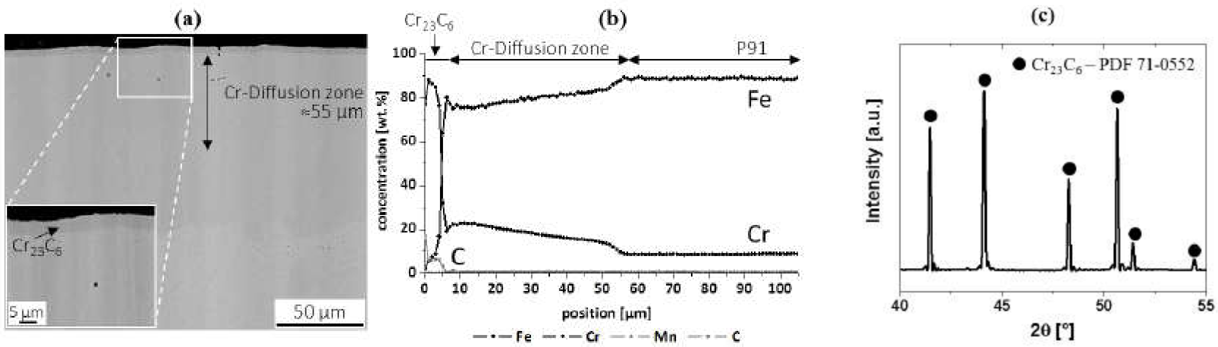


Figure 17: a)Cross-sectional back-scattered electron (BSE) image; b) elemental line-scans of acquired by electron microprobe analysis (EPMA); c) X-ray diffraction (XRD) pattern of the DFI2 coating deposited on T91.

The results of the static long term tests are shown in Figure 18, where also the performance of nickel base alloys Inconel617 and Haynes 230 was included for comparison. The results show **excellent performance of the coatings with negligible mass changes compared to non-coated substrates even after 10,000h of testing at 580°C in solar salt**.

[9] ISO17245:2015, Corrosion of metals and alloys - Test method for high temperature corrosion testing of metallic materials by immersing in molten salt or other liquids under static conditions

[10] P.Audigié, et. al (2018): High temperature molten salt corrosion behavior of aluminide and nickel-aluminide coatings for heat storage in concentrated solar power plants. Surface and Coatings Technology, 349, 1148–1157. doi:10.1016/j.surfcoat.2018.05.081

[11] D. Fähsing et. al (2018). *Corrosion testing of diffusion-coated steel in molten salt for concentrated solar power tower systems. Surface and Coatings Technology.* doi:10.1016/j.surfcoat.2018.08.097

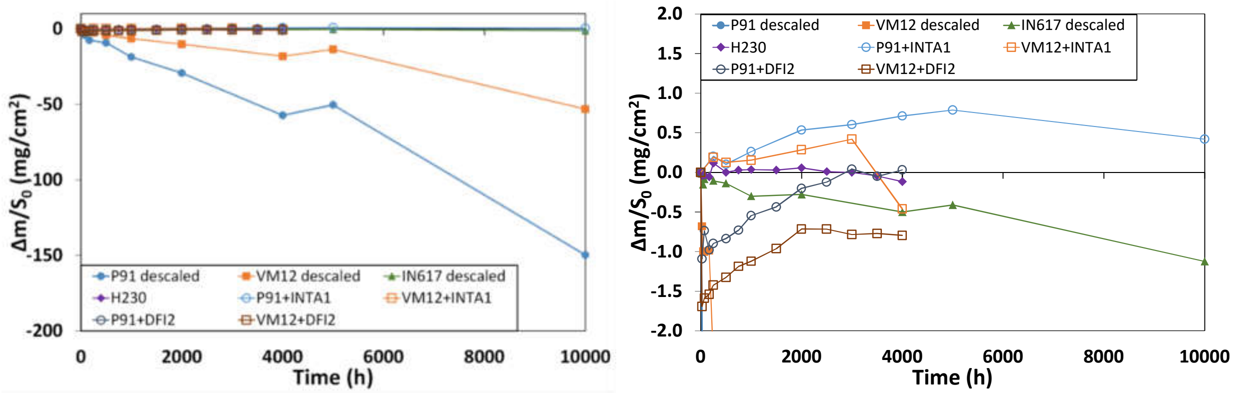
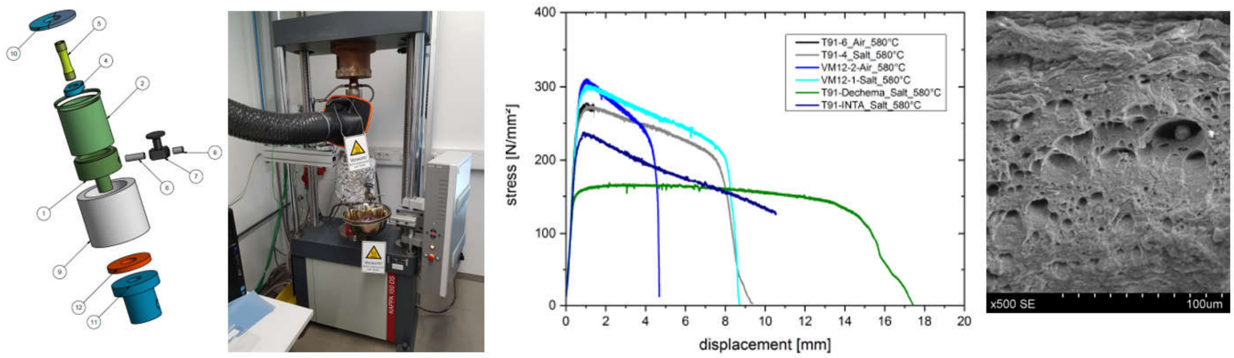


Figure 18 : Gravimetric analysis comparison between coated P91 and VM12 by INTA and DECHEMA versus uncoated substrates and nickel base alloys in contact with Solar Salt at 580°C under static conditions up to 10,000 h: (a) full data range (b) zoom-in at smaller mass changes.

In addition, the best selected coated materials (INTA1 and DFI2 on both T91 and VM12) have a much better behavior in contact with molten salts than uncoated substrates under **cyclic conditions (300-580°C in solar salt) and under dynamic conditions (salt flow rate of 0.2m/s at 580°C)**. From a corrosion point of view, the INTA1 coating was very stable, maintaining its morphology and composition whatever the test conditions. Only a very thin oxide scale was observed after long term exposure. The DFI2 coating developed a thicker oxide and evidenced local attacks of corrosion which probably leads to a shorter lifetime.

In addition, **slow strain rate tests (SSRT)** have been carried out at 580°C in air and in salt KNO_3 / $NaNO_3$ (40/60). A test setup was designed and built to conduct mechanical tests in molten salt, see Figure 19a and b. The aim was to test samples in industry-oriented conditions where mechanical loads and corrosive attack from the salt can be present simultaneously in a tensile testing device. The test time achieved was up to 40 days for the sample T91-DFI2 (here named T91-Dechema) in salt until it ruptured. During the test, the time, displacement of the crosshead of the tensile testing device and the force is recorded. Figure 19c shows the resulting plot of stress versus displacement. Whereas the T91 samples tested in salt and tested in air show exactly the same yield stress, the coated samples differ significantly from this behavior. The mechanical properties changed during the coating process. An important outcome of the tests is that no stress corrosion cracking could be observed for VM12 and T91, which would result in fracture without significant plastic deformation. The fracture surface of a sample tested in salt can be seen in Figure 19d. Samples from T22 could not be tested, as corrosion was too severe.



a b c d

Figure 19 Slow strain rate tests (a) layout of the test setup and (b) picture of the test rig; (c) results from the SSR tests, the stress versus displacement is shown; (d) ductile fracture is observed, as can be seen e.g. on surface of VM12 tested in salt

Chlorides and sulphates are common salt impurities and have a big influence on the chemical and thermal stability of the salt and its corrosive effect. UCM found similar corrosive behavior for 300 and 500 ppm of Cl^-/SO_4^{2-} impurity levels on T91, while 700 ppm was more aggressive. DFI found lower corrosion rates in solar salt with 300 ppm impurities than for Solar Salt with 100 ppm impurities and explained this behavior by the formation of stable $CrCl_2$ at the scale-metal interface. However, further increase of chlorine content could lead to “active oxidation” and a catastrophic loss of wall thickness. Also it was found that an increase of impurity levels leads to a reduction in both freezing point and degradation temperature of the salt. The impurity level of 500 ppm Cl^- and 500 ppm SO_4^{2-} seems to be a good compromise, both from a corrosive and economic point of view. In addition, this impurity level only reduces the working-temperature range in 4 °C and was therefore selected to be used for the corrosion tests carried out on the weld joints.

Different corrosion tests were performed under cyclic, static and dynamic conditions up to 1,000 hours in order to assess the effects of molten salts on the Heat Affected Zone (HAZ) of weld joints, see Figure 20. The best coatings from the previous corrosion test were selected: P91-IN617; **DFI2**- (P91-IN617) and **INTA**1- (P91-IN617). Gas tungsten arc welding (GTAW), also known as tungsten inert gas (TIG) welding was used for the manufacturing of the weld joints between T91 and IN617. The preparation of the weld bevels was carried out at Vallourec Research Center Germany. Finally, the entire weld joint was subjected to a post weld heat treatment (PWHT) in a furnace. The PWHT selected for the dissimilar weld is always selected based on the weakest material, in this case T91. An example of the samples prepared are shown in Figure 20.

The normalized weight change versus time in three conditions are shown in Figure 21. It can be seen that regardless of the type of the coating, **coated weld joint samples showed a very stable behavior up to 1000 h**, whereas the uncoated weld joint exhibited fluctuations in the weight change diagram. Cr-diffusion coated T91/IN-617 samples showed a slight mass loss in the early stages of the exposure which is associated with the dissolution of the pristine $Cr_{23}C_6$ layer. Similar to the DFI-chromized samples after their initial mass loss, INTA-aluminized samples showed a negligible weight change which can be interpreted as a highly protective behavior.

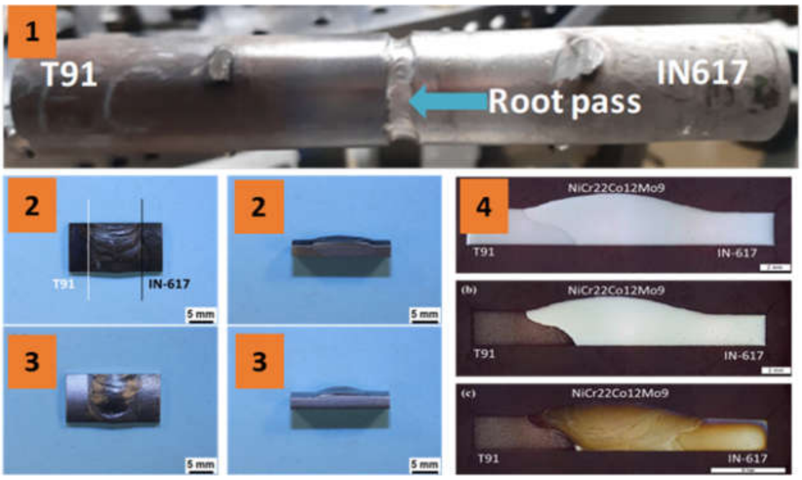


Figure 20. 1. Root pass of the weld joint T91-IN617; 2. Top and side views of the T91/IN-617 weld joint coupon sample in the as-manufactured condition and 3 after glass-bead blasting; 4. Cross-sectional images of T91/IN-617 weld sample, non-etched, V2A-pickle etched and 10% oxalic acid aqueous solution etched conditions.

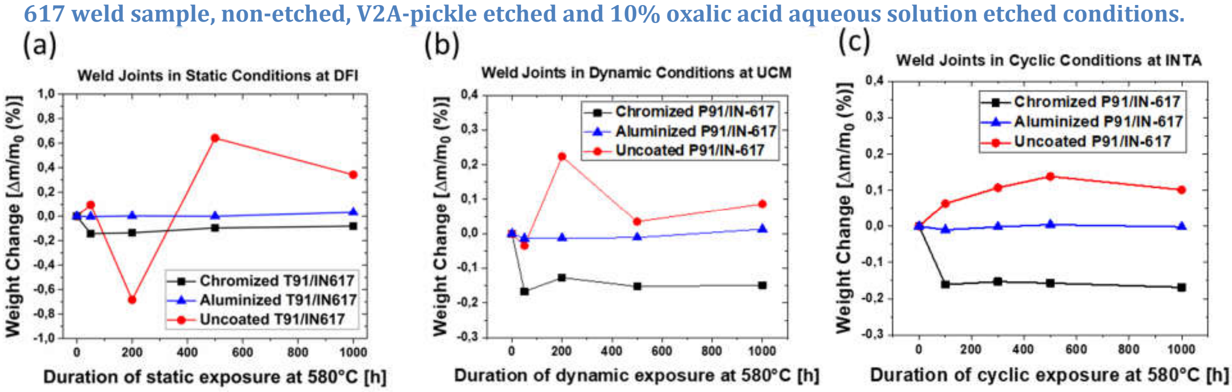


Figure 21. Normalized weight change as a function of duration of exposure test for uncoated, chromized and aluminized T91/IN-617 weld joint samples under a) static (b) dynamic and (c) Cyclic conditions.

UCM developed an **on-line corrosion monitoring** system, based on electrochemical measurements, more specifically on Electrochemical Impedance Spectroscopy (EIS) measurement[12]. EIS is a non-destructive technique typically implemented by applying a series of sinusoidal potential fluctuations at amplitudes of ± 5 to 10 mV about the free-corrosion potential and at frequencies in the range of 10-3 Hz to 50 - 100 kHz. This technique shows good results when it is used to characterize the interface between a metal and a conductive solution. In these cases, it provides information about the corrosion mechanisms that are occurring in the metal and also if the conductive solution is suffering changes that affect its physical properties. Thy novel characterization technique has been used to measure a corrosion rate of 300 µm/year of P91 steel at 580 °C in contact with solar salt.

2.5 Overview of progress compared to the state of the art and KPIs

Table 4 shows the target and actually achieved KPIs in the RAISELIFE project. Table 5 shows the increase in Technology Readiness Level (TRL) and Manufacturing Readiness Level (MRL) of the different material developments throughout the project.

The same content of Table 5 is displayed graphically in Figure 22.

Table 4: KPIs of RAISELIFE materials (T is temperature, ρ is reflectance, α is absorptance, ε is emittance and τ is transmittance)

KPI of materials before RAISELIFE started	Target KPI within RAISELIFE	Final value achieved after 48 months of project implementation
4 mm glass mirrors: ρ=94.5%, lifetime >10 years in corrosion class ≤C2	ρ =94.5%, lifetime >10 years in corrosion class ≤C3 (low-cost coating) and ≤C5 (high protective coating)	Low-cost coating (2 paint layers): ρ =95.0%, ρ remains above 90.0% for 16-21 years in C3 and for 8-14 years in C4. High protective coating (3 paint layers): ρ=95.0%, ρ remains above 90.0% for more than 25 years in C3 and C4.
Ultra-thin-glass mirror: ρ >96.5%, lifetime >10 years for all subcomponents	ρ >96.5%, lifetime >2 years proven in-service for the integrated system	ρ =96.0% for 0.2mm mirrors (wet silvering process) Lifetime: ρ remains >96% after exposure of 2 years in different sites of corrosivity class C2-C4. The backside composite structure proofed to provide additional corrosion protection.
Secondary high-temperature mirror: ρ =95.0%, stable for 1 month at 350°C under lab conditions	ρ =95.0%, lifetime > 2 years proven in-service	ρ=95.5 %, 46 days tested under real operation conditions (380°C, 350kW/m^2, 155 hours, 388 cycles) with degradation to ρ=93.7% Second, more durable development proofed to be stable for >2 months @ 450°C in muffle furnace test, but initial ρ only reaches 92%.
Cost of 4 mm glass mirrors: 16.0 €/m^2	4 mm glass mirrors: 15.8 €/m^2	4 mm glass mirrors: 12 €/m^2 1 mm glass mirrors: 13 €/m^2 (when purchasing more than 1.500.000m^2)
Anti-soiling coating for mirrors: Increase of average solar field reflectance of 1-2%	Increase of average solar field reflectance of 2% with a proven lifetime >7 years	Increase of average of solar field cleanliness of +0.8% for coating AS1 for pressurized water cleaning and +0.5% for coating AS2 for brush cleaning after 22 months of exposure at PSA. AS1 showed a disadvantage of -0.9% for brush cleaning and AS2 of -0.5% with pressurized water, mainly due to degradation in form of abrasion. The second set of coatings (G, GF) showed an increase in cleanliness for both cleaning methods after 14 months without apparent degradation. Pressurized water: G: +1.6%, GF: +1.2%; Brush: G: +0.9%, GF: +0.6%

[12] V. Encinas-Sánchez et. al (2019): Electrochemical impedance spectroscopy (EIS): An efficient technique for monitoring corrosion processes in molten salt environments in CSP applications. Solar Energy Materials and Solar Cells, 191, 157–163. doi:10.1016/j.solmat.2018.11.007

KPI of materials before RAISELIFE started	Target KPI within RAISELIFE	Final value achieved after 48 months of project implementation
α=94%; stable for 1700 h at 650°C for selective coatings: ε=32% for ceramic paints: ε=75%	α=96%; lifetime >10 years at T=600°C ε<35% (selective coating) ε<75% (non-selective coatings)	*Non-selective coatings BSII, INTA+BSII:* • α=97.2%; ε=89.5%, lifetime (= time for which α>95%) 15 years at T=720°C (molten salt receivers, substrate Inconel 617) • α=96.4%; ε=78.4%, lifetime 7 years at T=600°C (steam receivers, substrate T91) *Non-selective coating DFI:* • α=94.6%; ε=85.9%, performance criterion not met (for both Inc617 and T91). Good stability under accelerated aging tests. *Selective coating Fraunhofer:* • α=94.9%; ε=26.8%, performance and lifetime criterion not met (for both Inc617 and T91)
Non-evacuated receivers for linear concentrators, sol-gel based: α>92% (in service) ε=13% (250°C) CNT-based: α=94% ε=23% (200°C)	Non-evacuated sol-gel based receivers: α>95.5% (in service) ε=8% (250°C) Non-evacuated CNT-based receivers: α= 96% ε=15% (200°C)	*Sol-gel based (CIEMAT):* *Chromium plated steel:* α=95.5%, ε=9.1% (250°C) Coating stable for >15 months in furnace at 400°C without degradation, negligible degradation after 14 months of field testing at 180°C by Soltigua. *CNT-based (HUJI) on stainless steel* α=96.6%, ε=80.0% (20°C) Coatings with intermediate ITO layers (for reduced emittance) not stable
Transmittance of anti-reflective coated glass envelope tubes for evacuated receivers for linear concentrators: τ>96%	τ >97% with increased abrasion resistance by factor 30	τ =97.2% with increased abrasion resistance by factor 2.5 (verified in Taber Abrasor test, in which it takes 100 cycles to remove the coating completely). High stability against accelerated humidity tests. Transmittance stayed between τ =95.1% - 96.1% after 12 months of field testing at Soltigua at 180°C, including 2 cleaning cycles per month.
Aluminide coating for steels: >80,000h under steam at 650°C (lab test), >22,000 h under high pressure steam (plant test) Multi metallic diffusion coating: >10,000 h under steam at 700°C, weldable	Lifetime >10 years in molten nitrate environment	*Aluminide diffusion coating (INTA):* Stable up to 10,000h in solar salt at 580°C. No significant mass loss detected of coated samples, whereas the uncoated P91 and VM12 have lost 193µm and 68µm respectively after 10,000 hours at 580°C. *Chromium diffusion coating (DFI):* Stable behaviour up to 1000 h of isothermal exposure in molten solar salt at 560°C as well as up to 4000 h of isothermal and dynamic and 400 cycles of thermocyclic exposure in molten solar salt at 580°C. Coated samples showed an initial mass loss due to the dissolution of the carbide layer followed by parabolic mass increase in all testing conditions. In addition, chromium diffusion coating exhibited high fracture strain during tensile tests with in-situ exposure to molten solar salt at 580°C. Furthermore, Cr-diffusion coated T91/IN-617 weld joints showed a significantly higher molten nitrate corrosion resistance compared to their uncoated counterparts at 580°C under static, dynamic and thermocyclic conditions up to 1000 h. Particularly, the scaling behavior of the T91 side of the weld joint is substantially improved via Cr-diffusion coatings.

Table 5 : Materials tested in RAISELIFE and their TRL/MRL increase achieved throughout the project

Type	Development	Start		End	
		TRL	MRL	TRL	MRL
Reflector coatings	Anti-soiling (AGC, coatings GF, G)	3	5	5	5
	Hard-coating (AGC)	3	5	4	5
	Low-cost mirror coating (AGC)	4	7.5	6	7.5
	Anti-soiling (HUJI)	3	4	5	4
	Secondary Mirror (Fraunhofer)	4	1	5	4
Molten salt coating	Slurry aluminide coating (INTA)	3	5	4	5
	Pack cementation coating (DFI)	3	5	4	5
Receiver coating (solar tower)	Ceramic spray coating (BSII)	6	7	8	8
	Slurry aluminide primer (INTA) + BSII top coat	4	5	5	5
	Pack cementation coating (DFI)	4	5	5	5
	Selective coating (Fraunhofer)	4	5	5	5
Receiver coating (line focussing)	Anti-Reflective coating (Ciemat)	5	7	7	8.5
	Sol-gel coating (Ciemat)	5	4	7	5.5
	Carbon Nanotube coating (HUJI)	3	4	4	4

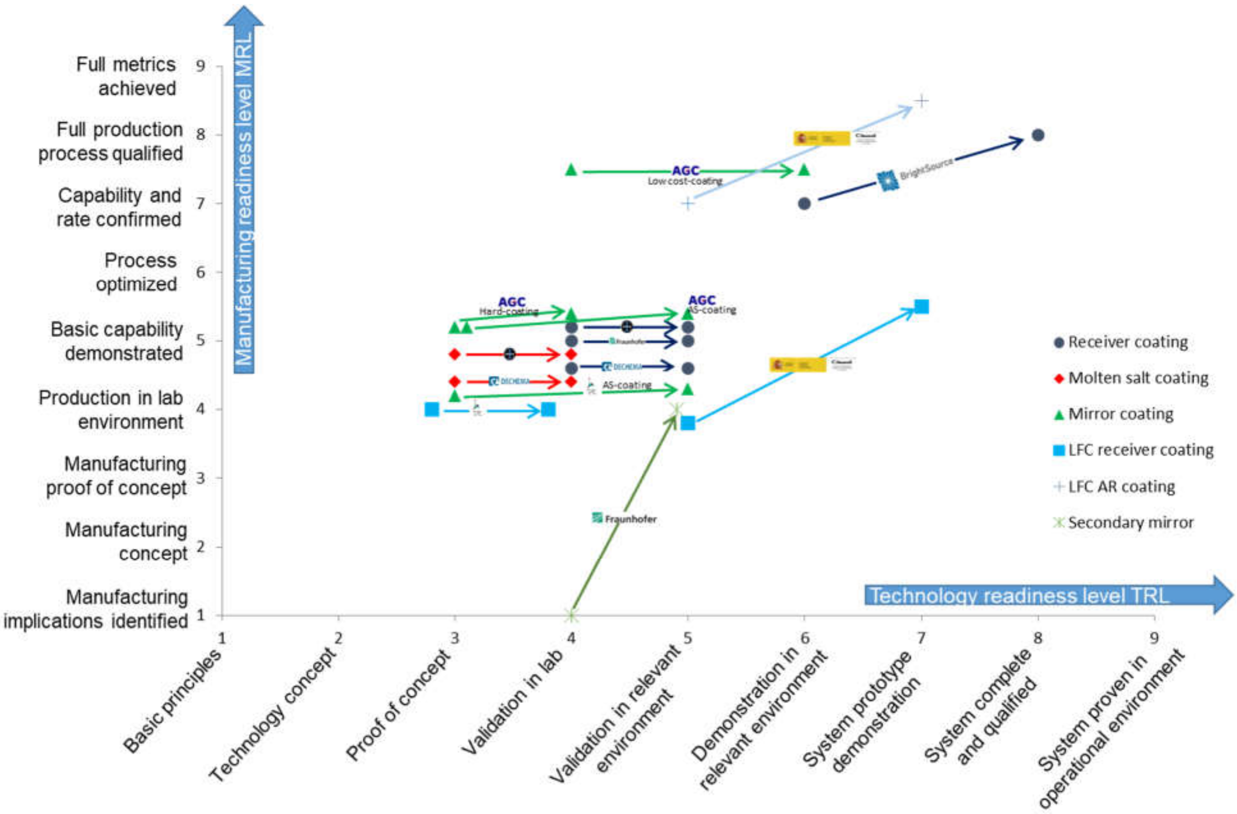


Figure 22 : TRL/MRL increase of different material developments achieved in RAISELIFE

3. Exploitation and dissemination

3.1 Exploitation

CSP market potential

In the current CSP domain it would be pretentious to assume accurate market potential. Major achievement to quote is the already built capacity pf 6GW$_e$ (above 2GW$_e$ in USA, 3GW$_e$ in Spain, 0.5GW$_e$ in Morocco and China) and about worldwide 1.5GW$_e$ under construction. As per the future, down tone declarations apart for planned +5GW$_e$ in Spain, additional 1.6GW$_e$ are under development (1.1GW$_e$ in Chile, 0.4GW$_e$ in South Africa and Australia). For future potential of RAISELIFE domains, outlined by its industrial partners, a market range of 3.7GW$_e$ to 20GW$_e$ has been assumed.

As per solar process heat, Soltigua quotes a potential market size of 0.9 GWh$_{th}$/year, which at a cost of heat of 3 €cent/kWh$_{th}$ is worth approx. 27 million €/year.

RAISELIFE exploitable results

The products ready for market, exploitable services emerging from methodologies developed in RAISELIFE and possible future exploitable products are listed in Table 6, Table 7 and Table 8. The list of exploitable results have been filed in the EERA IP repository and disseminated via a brochure to CSP stakeholders.

Table 6 : Products ready for market

No.	Product	Improvement compared to state of the art	Contact person
1	Absorber coating for tubular solar tower receiver	α_s = 97.2%, ε = 89.5% (750°C) T_{max}= 750°C (Inconel617); 650°C (T91/VM12) Lower degradation rate than Pyromark2500	Mr. Yaniv Binyamin ybinyamin@brightsourceenergy.com Dr. Alina Agüero Bruna agueroba@inta.es
2	Absorber coating for tubular solar tower receiver	α_s = 94.6%, ε = 85.9% (750°C) T_{max}= 750°C (Inconel617); 650°C (T91/VM12) Lower degradation rate than Pyromark2500	Dr. Mathias Galetz galetz@dechema.de
3	Low-cost selective sol-gel absorber coating for non-evacuated parabolic trough receiver	α_s =95.4%, ε=7.8% (250°C) T_{max}= 400°C (stable for >15 months in furnace at 400°C without degradation).	Dr. Angel Morales Sabio angel.morales@ciemat.es
4	Anti-reflective coating for glass-envelope tube for evacuated parabolic trough receiver	τ_s =97.2% Improved abrasion resistance by factor of 2.5 compared to the state of the art.	Dr. Angel Morales Sabio angel.morales@ciemat.es
5	Low-cost protective coating for solar mirrors	2-layer instead of 3-layer coating systems for cost savings in dry desert sites of low corrosivity. Reflector cost about 12€/m².	Mrs. Anne Attout Anne.Attout@eu.agc.com
6	Coating to prevent steel corrosion in molten salt	Negligible mass loss of coated ferritic steel after 10,000 h of furnace testing in solar salt at 580°C.	Dr. Alina Agüero Bruna agueroba@inta.es Dr. Mathias Galetz galetz@dechema.de
7	VM12-SHC steel qualified for CSP application	VM12-SHC may be employed in the low-temperature part of molten salt receivers instead of T91. Corrosion layer of VM12-SHC is 68µm compared to 193µm of T91 after 10,000 h of testing in solar salt at 580°C.	Dr. Javier Piron javier.piron@vallourec.com

Table 7 : Services ready for market

No.	Service	Improvement compared to state of the art	Contact person
1	FREDA measurement system	Assess heliostat degradation of entire solar field.	Mrs. Anna Heimsath anna.heimsath@ise.fraunhofer.de
2	TraCS measurement device	Automatic collection of continuous soiling data on reflectors.	Dr. Fabian Wolfertstetter fabian.wolfertstetter@dlr.de
3	Sensor to monitor corrosion rates of steels in molten salt	Automatic collection of continuous corrosion data of structural materials.	Prof. Francisco Javier Pérez Trujillo fjperez@quim.ucm.es
4	Automatic coating machine of HSA absorber coating	Minimizes production cost, increases coating lifetime by homogeneous deposition, avoiding hot-spots (coating thickness tolerances of 5µm were achieved compared to 20µm with manual painting).	Mr. Yaniv Binyamin: ybinyamin@brightsourceenergy.com
5	Testing methodology for absorber coatings for solar tower receivers	Testing under concentrated solar flux and in climate chambers.	Dr. Florian Sutter florian.sutter@dlr.de Dr. Bernard Claudet claudet@univ-perp.fr
6	Testing methodology for secondary mirrors for solar tower	Testing under concentrated solar flux and in climate chambers.	Dr. Aránzazu Fernández-García arantxa.fernandez@psa.es
7	Testing methodology for primary mirrors	Outdoor exposure and climate chamber testing. Lifetime prediction based on accelerated aging testing.	Dr. Florian Sutter florian.sutter@dlr.de Dr. Aránzazu Fernández-García arantxa.fernandez@psa.es Dr. Sanae Naamane s.naamane@mascir.com
8	Testing methodology for anti-soiling coated mirrors	Outdoor testing in Spain and Morocco with regular cleaning intervals. Climate chamber testing.	Dr. Florian Sutter florian.sutter@dlr.de Dr. Aránzazu Fernández-García arantxa.fernandez@psa.es Dr. Sanae Naamane s.naamane@mascir.com
9	Testing methodology for corrosion in molten salt	Furnace and slow strain rate (SSRT) testing in molten salt at different temperatures.	Prof. Francisco Javier Pérez Trujillo fjperez@quim.ucm.es Dr. Alina Agüero Bruna: agueroba@inta.es Dr. Mathias Galetz: galetz@dechema.de Dr. Johannes Preußner johannes.preussner@iwm.fraunhofer.de
10	System simulation tools	Allow for economic assessment of novel materials, receiver and solar field efficiency computation.	Theda Zoschke theda.zoschke@ise.fraunhofer.de Ralf Uhlig Ralf.Uhlig@dlr.de

Table 8 : Preliminary products with further optimization or testing needs

No.	Product	Improvement compared to state of the art	Contact person
1	Selective absorber coating for tubular solar tower receiver	α_s = 94.9%, ε = 26.8% (750°C) T_{max}= 750°C (Inconel617); 650°C (T91/VM12) Durability needs to be optimized	Dr. Christina Hildebrandt christina.hildebrandt@ise.fraunhofer.de
2	Low-cost absorber coating for non-evacuated parabolic trough receiver	α_s=96.6%, ε=80.0% (20°C) Carbon nanotube based spray-coating. Durability and thermal emittance need to be optimized	Prof. Daniel Mandler daniel.mandler@mail.huji.ac.il
3	Anti-soiling coating for solar mirror	Increased cleanliness of solar field up to 1.6% after 14 months of outdoor testing without degradation.	Mrs. Anne Attout Anne.Attout@eu.agc.com Prof. Daniel Mandler daniel.mandler@mail.huji.ac.il
4	Ultra-thin glass mirror of high reflectance	200µm flexible glass mirror with solar reflectance of ρ=96% (1.5%-p higher than state of the art reflectance).	Dr. Michel Prassas PrassasM@corning.com
5	High-reflectance composite heliostat	Low-weight due to composite material; 0.5pp higher reflectance due to first surface mirror; superior corrosion resistance; able to withstand wind speeds >45m/s; 30% cost reduction down to 45€/m² heliostat surface (including backing structure)	Mr. Yaniv Binyamin: ybinyamin@brightsourceenergy.com Mr. Yoel Gilon: ygilon@brightsourceenergy.com

The industrial partners of RAISELIFE evaluated their exploitation plan, expected revenues and market share.

BrightSource will exploit their receiver coating developed and tested in RAISELIFE in the DEWA Dubai 100MW solar tower project with 15 hours thermal storage (1000m² surface equivalent to 1 Mio.€ value). The coating of above 97% absorbtivity performed supremely under solar and accelerated tests and BrightSource envisages to supply this coating to 37-200 CSP plants depending on the technology uptake. Dechema filed a patent on their absorber coating development and is ready to license it to potential customers.

Mirror supplier AGC intends to strengthen its position as market leader by promoting reliable mirrors with proven durability, expecting a sales volume of 7,000 km² until end of 2025. Promising potential for thin-glass composite mirrors obtained both in full scale protype heliostat and lab, which requires a follow up project to be fully exploited by BSII. Mirror testing methodologies for optical quality and durability can be exploited in form of industry services by DLR, CIEMAT, MASCIR and Fraunhofer.

Vallourec adapted its exploitation strategy adding Ni-base 617 seamless tubes from one of its subsidiary Valinox to their product portfolio, since recent discussions with solar tower designers have shown that the design has evolved to be 100% of Ni-base tubes without any need in steel tubes anymore.

The protective coatings for molten salt tubes, pipes and others containers of molten salt could be a promising development, since they survived 10,000h of testing at 580°C in molten salt without mass change. Correspondingly here as well further project could follow to demonstrate the coatings under solar operation and as applied on full sized tubes.

In terms of the process heat market, the novel receiver coatings developed by CIEMAT within RAISELIFE could be commercialized through Soltigua's sales network. But while low oil prices remain low, Soltigua intends to continue to target specific niche segments and developed a complementary, synergic business line with solar PV trackers.

3.2 Dissemination

RAISELIFE website

The project website was launched on 29th of June 2016. It is a comprehensive website set up for both consortium members (partners only area) and public access. It provides an overview of the project and information on the activities being carried out. Of special interest are the repository included in the partners-only area to store all the relevant documents of the project and share the information among the partners, and the different tools provided to the partners to report all the dissemination and related activities.

The use of the project website has increased as the project has progressed and the consortium partners have realized its usefulness to inform about the different activities carried out in the framework of the project, i.e. dissemination and related activities and exploitation activities, as well as to propose some others. Furthermore, it has been used to plan the dissemination activities of the partners, and to publicize the progress of project activities through the newsletters and the publishable deliverables. In addition, the presentations of the RAISELIFE dissemination workshop have been uploaded on the public section of the website.

Promotional material

A leaflet was designed, printed and distributed among the partners for further dissemination of the activities of the project. These leaflets were distributed in events in which partners participated, either as a speaker or as author of a poster in a conference, workshops, etc. They were also distributed among the attendees of the two public workshops organised during this project. In addition, a project folder was designed, printed and distributed during the two workshops, along with silkscreened pens. Also a project roll-up was designed and used during these two workshops scheduled.

Social networks (Twitter, LinkedIn) have been used throughout the project to promote the different activities of the project in terms of dissemination of events and publications.

An article on the RAISELIFE project, titled 'RAISELIFE project extends the lifetime of functional materials for Concentrated Solar Power Technologies', was published in the autumn edition of the European Energy Innovation magazine at www.europeanenergyinnovation.eu.

A brochure was prepared and published on the Project website on February 2020, with the products and services that have resulted from the implementation of the RAISELIFE Project activities, which can be found on the Project website at https://www.raiselife.eu/.

Publication of RAISELIFE results

The results of the project have been disseminated in the form of oral presentations and posters at several conferences and workshops. Many of these presentations have led to the publication of articles in different journals, i.e. Solar Energy, Solar Energy Materials and Solar Cells, and Surface and Coatings Technologies, and in the SOLARPACES conference proceedings (years 2017-2019).

A total of 13 articles have been published in peer-reviewed journals, while publications in conference proceedings and or workshops amount to 18 (see Table 9).

Table 9 : Number of publications linked to the project

Peer-reviewed	13
Conference proceedings/workshops	18
Total	31

A summary of the dissemination carried out during the implementation of the project can be found in Table 10 and in each of the periodic reports submitted to the EC. Similar activities (e.g. participation to trade fairs and solar industry events) have been attended by industrial partners as part of the exploitation activities (e.g. to assess market potential of exploitable results).

Table 10 : Number of dissemination and communication activities linked to the project

Type of activity	Number of activities
Non-scientific and non-peer-reviewed publication (popularised publication)	3
Oral presentation to a scientific event	3
Oral presentation to a wider public	1
Organisation of Conference	1
Organisation of Workshop	2
Participation in activities organized jointly with other H2020 projects	1
Participation to a Conference	38
Participation to a Workshop	27
Participation to an Event other than a Conference or a Workshop	9
Posters	1
Press release	8
Training	1
Trade Fair	1
Web sites/Applications	5
Total	100

Organization of RAISELIFE events

The 1st Dissemination workshop on Raising the Lifetime of Functional Materials for Concentrated Solar Power Technology was held on 17th of May 2017 at Universidad Complutense de Madrid (UCM), Madrid (Spain). The 2nd workshop was held on 28th November 2019 at Vallourec Deutschland GmbH in Dusseldorf (Germany). The results of the RAISELIFE project were presented to the audience during these sessions. The sessions focused on how the project results could help in the development of standards. In the afternoon, a World Café was organized to allow discussing the different topics presented by the RAISELIFE consortium members in small groups while having the coffee break. This provided the possibility to compare the methodology and results with the external attendees of the workshop. Main points of discussion were: testing conditions for absorber coatings under high flux, the influence of different salt composition and additives on the corrosion rates, the performance and durability of reflectors and anti-soiling coatings, the main degradation types experienced in the plants, standardization and best practices and how degradation is considered in financial models. In 66 persons participated in the first workshop, while the second workshop counted 75 attendants.

3.3 Socio-economic impact

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, anti-soiling coatings, selective and non-selective receiver coatings, as well as corrosion resistant steel coatings to use with molten salt. The 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.

The techno-economic assessment was conducted for the different material developments showing the impact of degradation on the LCOE of CSP plants. Therefore degradation models were derived from accelerated aging and on-site tests. These models were implemented in a dynamic system simulation environment. The resulting energy yield is used to calculate the LCOE and IRR and compare the different materials.

A simulation tool chain was developed to quantify the impact of the new material developments of the RAISELIFE project in plant operation. This tool chain consists of the Fraunhofer ISE raytracing software Raytrace 3D, the DLR thermal efficiency FEM model ASTRID and the Fraunhofer ISE dynamic system simulation tool ColSim CSP.

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[13], 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.

With the ASTRID© approach by DLR[14], 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[15] 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.

The Fraunhofer ISE simulation software ColSim[16] 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, the simulation environment ColSimCSP was adapted to the material development models mentioned above. For the evaluation of heliostat coatings, the reflectance loss over time was considered for different material developments, but also for different corrosion and erosion classes. Also anti-soiling coatings were evaluated by taking into account varying soiling factors and always considering a cleaning frequency of 14 days. 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 heliostat field consists of 72,000 heliostats of 20.8 m².

The economic impact of each material development is assessed. For each simulation scenario, the

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13 P. Schöttl, K. Ordóñez Moreno, F. C. D. van Rooyen, G. Bern, and P. Nitz, "Novel sky discretization method for optical annual assessment of solar tower plants," *Solar Energy*, vol. 138, pp. 36–46, 2016, doi: 10.1016/j.solener.2016.08.049.

14 C. Frantz, A. Fritsch, and R. Uhlig, "ASTRID© – Advanced Solar Tubular ReceIver Design: A powerful tool for receiver design and optimization," in *AIP Conference Proceedings 1850: International Conference on Concentrating Solar Power and Chemical Energy Systems*, Abu Dhabi, United Arab Emirates, 2017.

15 SAS IP, Inc., "ANSYS, Inc. Release 17.0 Product help: Chapter 6.5 – Radiosity Solution Method. Release 17.0,"

16 C. Wittwer, "ColSim - Simulation von Regelungssystemen in aktiven solarthermischen Anlagen," Universität Karlsruhe, Fakultät für Architektur, 1999. [Online]. Available: http://www.opticontrol.ethz.ch/Lit/Witt_99_PhD-UnivKarlsruhe.pdf

energy yield in each year of the plants lifetime is obtained. This energy yield is input to the calculation of economic key performance indicators like Levelized Cost of Electricity/Heat (LCOE/LCOH) and Internal Rate of Return (IRR). Apart from the material costs, the parameters for cost assessment are the same for all evaluations of one reference plant. This includes the life time of the plants, investment costs for all components apart from the evaluated material, operation and maintenance costs, averaged selling price etc. Replacement and recoating costs, replacement and re-coating costs are also considered.

Each material development was evaluated based on the developed degradation models and material parameters. As an example, the following graph shows the evaluation of different heliostat coatings (“RLA1”, “RLA3”, “RLA4”) and different corrosion classes (“C2”, “C3”, “C4”) for one erosion class (“E1”). The resulting energy yields after 30 years of plant operation and the resulting LCOE in different corrosion environments for each heliostat coating are presented. Compared with the state-of the art three-layer coating RLA1, slight improvements can be reached with the new two-layer coatings RLA3 and RLA4. The evaluation shows that the effect of better coating performance is more relevant than the cost reduction of two-layer coatings.

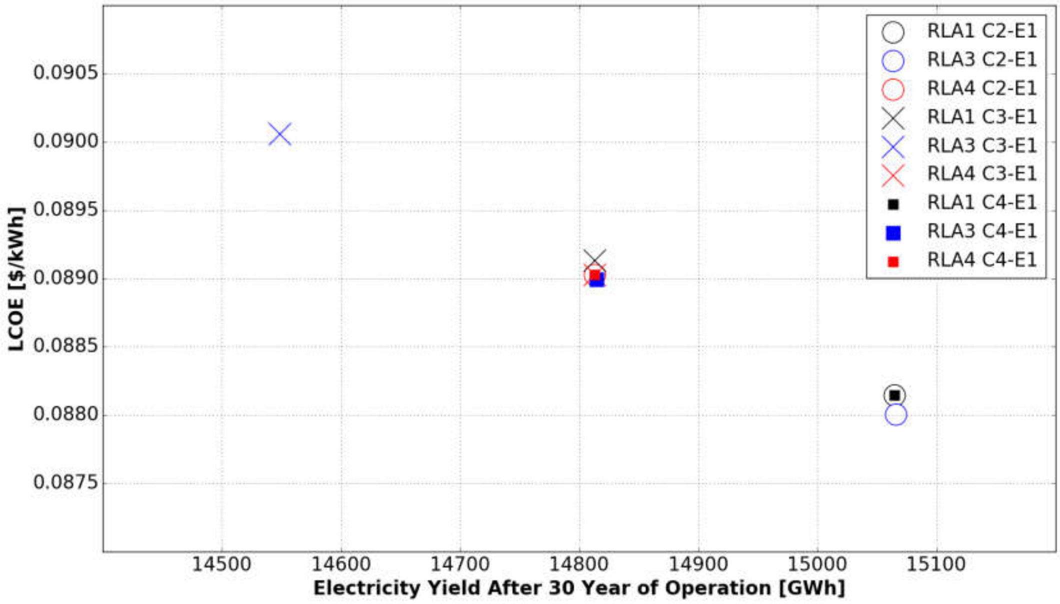

Figure 23: Energy yield and LCOE in different corrosion and erosion environments for various heliostat coating masterial developments

Further assessments of anti-soiling coatings and cost-saving composite mirrors were evaluated in the project and showed interesting improvements of the LCOE.

The results of the secondary mirror material degradation models showed significant degradation in only few years of plant operation. Therefore the material could not be applied in a system that operates 30 years. The evaluation of the secondary mirror therefore focused on the performance of a secondary mirror without considering degradation, showing the impact of energy yield as well as additional and saved costs on the plants LCOE. The simulations showed that the electricity yield could be increased by 1.57 %, given that the secondary mirror resists the high heat load. Due to a reduction in panel height also cost savings of the receiver can be expected, leading to a reduction of the LCOE of about 1.9%.

For the evaluation of receiver coatings, the absorptance and emmitance loss/increase over time was considered for different material developments. Also recoating processes of these receivers were considered. Therefore an optimization was conducted, to find the ideal recoating interval to reach the minimum LCOE. An exemplary case of one material development is shown in Figure 24. While the mean annual yield is the highest for three reapplications in a lifetime of 30 years (recoating interval of eight years), the LCOE is the lowest for one reapplication (recoating interval of fifteen years). From an economic point of view the optimal recoating interval is therefore fifteen years in this case. Compared to the case with no reapplication at all, the LCOE can be reduced by 0.1 %.

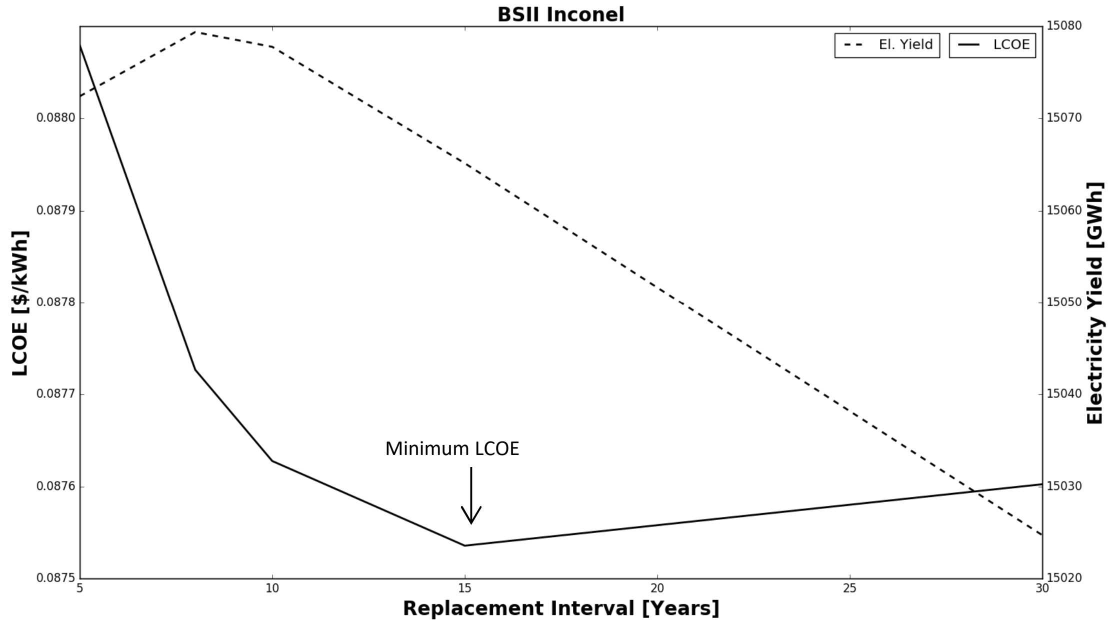

Figure 24 : Influence of number of replacements in 30 year life time on LCOE and mean annual yield

The LCOE for each receiver coating material development can be compared to each other. The following figure shows the energy yield and LCOE for various material developments. Only the scenarios with the ideal recoating interval, leading to the lowest LCOE are shown. The BrightSource Coating "BSII" and the Dechema coating "DFI" show the best results with high energy yield and lowest LCOE.

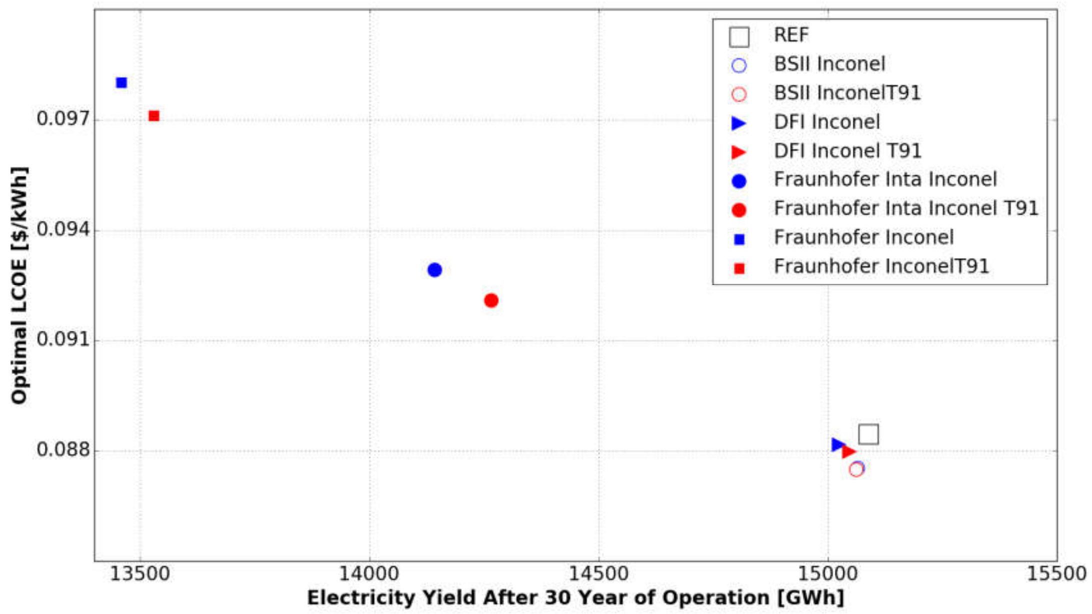

Figure 25 : Energy yield and LCOE for various receiver coating masterial developments

Additionally the usage of steel coatings to be able to use less costly steel in the storage system was assessed economically. Also an improved new salt mixture consisting of 45%$NaNO_3$/55% KNO_3 was evaluated and found to have a positive effect on the LCOE.

Finally a "best case" analysis was done, showing the impact of all best performing developments in the project RAISELIFE. Table 11 shows the summary of the case comparison. The electricity yield in 30 years could be increased by 1.5 % to 15099 GWh. The LCOE could be reduced by 9.8 % to 7.99 $Ct/kWh.

Table 11: Comparison of reference case and best case scenario

	Reference Case	Best Case	LCOE reduction
Protective Heliostat Coating	RLA1 (C2-E1)	RLA3 (C2-E1)	-0.2 %*
Composite Mirrors	No	Yes	-9.3 %*
Anti-Soiling Coating	Uncoated	AGC_G	-1.5 %*
Absorber Coating	Reference	BSII	-1.1 %*
Recoating Interval (Optimum)	5 years	15 years	
Cheaper storage + steel coating	No	Yes	-0.7 %*
Electricity Yield	14'880 GWh	15'099 GWh	
LCOE	8.86 Ct/kWh	7.99 Ct/kWh	**-9.8 %**
Additional option: Secondary Mirror	*No*	*Yes*	***-1.9 %***
Additional option: New salt mixture 45%$NaNO_3$/55% KNO_3	*No*	*Yes*	***-2.0 %***

**The individual reduction values do not necessarily add up to the total LCOE reduction because they refer to different reference values*

The evaluation of the RAISELIFE best case scenario shows that the LCOE can be reduced by almost 10 % compared to the reference scenario. The highest impact has the use of composite mirrors. Nevertheless, not all questions regarding the technical implementation have yet been clarified, for example how the different thermal expansion coefficients of the various materials affect the accuracy and durability. Also anti-soiling coatings that increase the average reflectivity have a high impact. The improved Brightsource absorber coatings show smaller degradation rates and therefore require less recoatings during the lifetime of the plant and therefore also have a positive impact on the electricity yield and cost calculation. Corrosion resistant steel coating and the less expensive 2-layer protective mirror coating also reduce the costs. Additional savings can be reached by applying a secondary mirror as the yield is increased and costs can be reduced. This LCOE reduction of 1.9 %, however, refers to another reference system design and therefore cannot be added to the list of total savings. The number gives a clear indication that a LCOE reduction can be reached based on the current assumptions, if a secondary mirror material is found that withstands the harsh temperature conditions. The same way, also the usage of a new salt mixture consisting of 45%$NaNO_3$/55% KNO_3 can reduce the LCOE further by 2.0%, but refers to another reference system with adapted operation temperature.

4. Conclusions

Among the highlights of the achievements of the RAISELIFE project the following points can be remarked:

- Qualification of a novel receiver coating developed by BSII, which will be employed in the commercial 100MW_e DEWA solar tower project in Dubai. The developed lifetime model predicts that the solar absorptance of the BSII coating will remain above 95% for about 7 years on ferritic steel substrate T91 (for steam receivers) and about 15 years on nickel base alloy Inconel 617 (for molten salt receiver). The higher lifetime compared to the state of the art Pyromark coating leads to a LCEO reduction of about 1.1%.
- Validation of durability of solar cured receiver coatings, opening the possibility to cure the coating directly on the top of the tower. This reduces expensive panel dismantling and furnace curing, fossil fuels (gas burners) as well as down-time of the power plant.
- From an economic point of view the optimum recoating interval of T91 receivers has been determined to be eight years by means of system simulation tools.
- An automatic coating machine prototype has been built which achieves 4 times lower thickness variation than manual painting and thus reduces possible hot spots in the coating.
- The price of solar mirrors can be reduced down to 12€/m² by using low-cost 2-layer coating systems, which showed to be as durable as 3-layer systems, with degradation rates of 2% in solar reflectance at exposure sites of corrosivity C2 after 20 years of exposure according to the developed lifetime models. In C3 environments, the degradation is slightly higher compared to 3-layer systems (4% vs. 2%).
- Design and construction of a composite thin glass heliostat for wind loads >45m/s at low weight and possible cost reductions of 30%, lowering expected heliostat cost from 68€/m² to about 45€/m².
- Anti-soiling coatings for the front glass of mirrors have shown to be able to increase the reflector cleanliness up to 1.5pp.
- Development of a selective receiver coating for non-evacuated line focusing receiver tubes operating up to 400°C. Negligible degradation after 18 months of in-service testing and >15 months of furnace testing.
- Improvement of the abrasion resistance of an anti-reflective coating for evacuated line focusing receiver tubes. The coating was deposited in an industrial coating line on a commercial receiver tube and was validated during 12 months of in-service testing. The coating is ready for commercialization.
- Development of weldable protective coatings for ferritic steels in molten salt environment, with high cost reduction potential compared to nickel base alloys. Stability proven for 10,000h during static and dynamic tests at 580°C in solar salt. Weld joints were tested up to 1,000h performing better than non-coated materials.
- Improvement of the durability of a novel high-temperature secondary reflector, albeit stability at 400°C has not been fully demonstrated. The secondary reflector has potential to increase the electricity yield by 1.57 % in the RAISELIFE reference solar tower plant, given that it withstands the high heat load.
- Publication of catalogue of best practices containing several testing and analysis methods of materials employed for CSP technologies
- Organization of two workshops for CSP stakeholders with around 70 participants each to disseminate the results achieved in the project

As one of RAISELIFE's primary goals, we projected that commercial implementation of the subject technologies could account for as much as 2.5-3 Euro-cent LCOE reduction per kWh of electricity produced for solar tower technology between 2015 and 2020. Back in 2015 when this goal was set, the typical LCOE of CSP systems was around 20 Euro-cents/kWh_e. Thus we aimed at reducing the LCOE by 12.5 - 15%. In the past years, the LCEO of CSP systems dropped significantly to 8.9 Euro-cents/kWh_e. On top of this reduction, it was shown within RAISELIFE that an additional LCOE reduction of 0.9 Euro-cents/kWh_e is possible using the novel material developments. This corresponds to relative LCOE reduction of 9.8%, thus almost achieving the initially set goal.