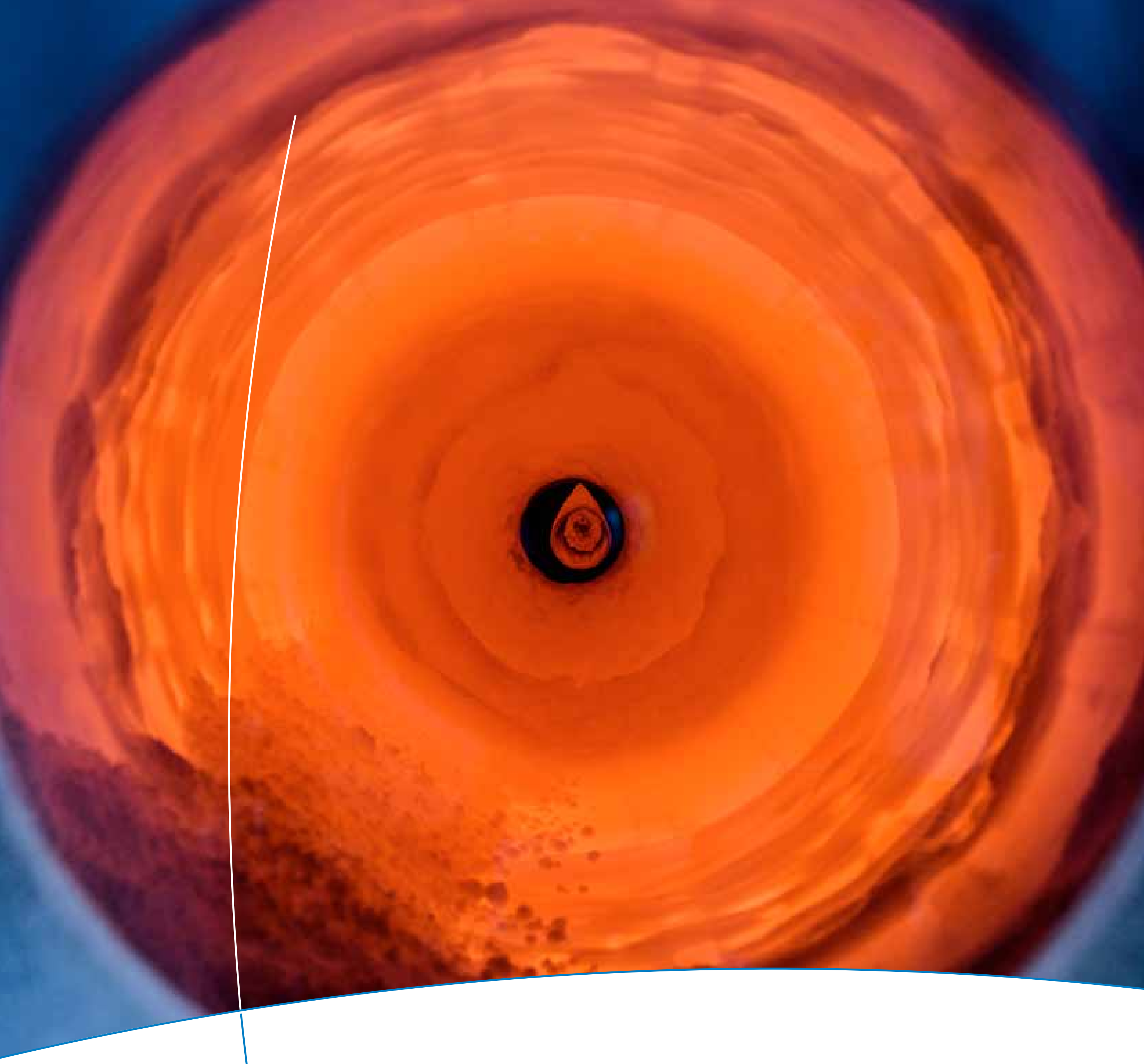


Institute of Solar Research
Status Report 2011 – 2019   Part I

DLR

Preface

This report gives an overview of the scientific and technical development and main results achieved within the first nine years of the Institute of Solar Research. It outlines the institute's organisational structure, its large-scale research facilities, cooperation and outreach activities. A list of our recognitions, awards, publications and patents is also included.

The institute emerged from the DLR Institute of Engineering Thermodynamics' Solar Research department in 2011 with 80 employees. With 25 million euros in start-up funding by the state of North Rhine-Westphalia, DLR purchased the demonstration Jülich Solar Tower Plant, founded the Institute of Solar Research, and constructed additional test facilities there.

From its beginnings in the 1980s, the institute built on DLR's excellent international reputation in research and development of concentrating solar thermal technologies. We created new test capacities to strengthen DLR's ability to innovate its future in solar tower technology, solar fuel production, sensor technology and thermal energy storage technologies. The expanded opportunities that these testing facilities made possible have significantly improved the conditions for industry-related CSP research and development in Germany. Today, more than 130 people work at the four locations in Cologne, Stuttgart and Jülich in Germany and Almería in Spain. At Jülich, a new DLR location with more than 30 employees was established; the Jülich solar power station has become a large-scale test site with extended capabilities.

Within the last nine years, the institute has delivered valuable scientific and technical contributions in materials development and characterisation, modelling and simulation, component qualification, advanced system design, testing and condition monitoring in concentrating solar technologies and beyond.

We would like to take this opportunity to thank all employees, customers, partners and supporters who have actively accompanied the Institute in its development. We look forward to continuing together on this path to further support the dissemination and success of concentrating solar systems as a sustainable energy technology option.

Robert Pitz-Paal and Bernhard Hoffschmidt
Directors

Prof. Dr.-Ing. Robert Pitz-Paal and Prof. Dr.-Ing. Bernhard Hoffschmidt, Directors at the Institute of Solar Research

Content

The Institute's Profile in Brief

Our research focus at DLR's Institute of Solar Research is on concentrating solar thermal technologies to provide dispatchable power (CSP), heat (CSH) or concentrated solar thermal (CST) fuels using solar chemical engineering. Our mission is to be a global leader for a sustainable future in the research, development and qualification of these technologies through strong system competence – from modelling to large scale research infrastructure, that allows researchers to assess technology improvements on a whole-system level.

This comprehensive range is what permits us to develop innovative ideas from lab bench scale to full scale ready to be put on the market. The high quality of our research is made possible through sophisticated research infrastructure and close cooperation with industry. In some cases, institute researchers have participated in projects of other research areas needed for a sustainable energy transition, for example applying a nowcasting system to PV systems control or performing condition monitoring in the building sector.

Today, the institute comprises 134 staff members, of which 87 are scientists. It is located at four sites, three of which are in Germany: Stuttgart, Jülich and the main site in Cologne. The fourth site is in southern Spain, at Almería where a permanent delegation of 25 people has access to the Plataforma Solar de Almería, Europe's largest research infrastructure on concentrating solar technologies, owned and operated by the Spanish research center CIEMAT.

The research activities are embedded in the DLR Energy programme, which allocates about 40 % of the institute's budget to internal projects or the co-financing of externally funded activities. This funding is granted by the Federal Ministry of Economics and Energy, based on a regular international assessment of the energy research program proposal organised by the Helmholtz Association. In the framework of this proposal, the institute cooperates closely with the Karlsruhe Institute of Technology (KIT) in the field of CSP technologies and with the Helmholtz Center Berlin in the field of solar fuels.

Internal cooperation with other DLR institutes takes advantage of specific relevant expertise:
– Thermal energy storage: Institute of Engineering Thermodynamics
– Gas turbine integration: Institute of Combustion Research
– Decarbonisation of industrial processes: Institute for the Decarbonisation of Industrial Processes
– Energy meteorology and monitoring of buildings: Institute of Networked Energy Systems
– Materials research: Institute of Materials Research
– Condition monitoring in the building sector: Institute of Optical Sensor Systems, Microwaves and Radar Institute, Remote Sensing Technology Institute, and German Remote Sensing Data Center

The institute has strong bonds with two universities. In joint appointments between DLR and RWTH Aachen, its directors, Robert Pitz-Paal and Bernhard Hoffschmidt are full professors in CSP. Christian Sattler, Head of the Department Solar Chemical Engineering holds a joint professorship in Solar Fuels between DLR and TU Dresden.

Cooperation with industry on the national and international level is driven mostly by joint project proposals to funding institutions, and provides more than 50 percent of the institute's budget. Approximately 10 percent of this comes from direct contracts for industry services.

Our strong collaboration with European and international research partners is made possible through a variety of networks and associations, in which members of the institute often take a coordination role. These networks are used to align research, develop joint research roadmaps, shape funding programmes and advise policy-makers. As an internationally visible research center, the institute is also active in countries that may become future markets for CSP technology. To help develop CSP in these countries, the institute offers training and research infrastructure, performs feasibility studies, and provides research cooperations and policy advice.

The Insitute of Solar Research has significantly shaped CSP technology development and cost reduction over the past decade. It has supported the dissemination of concentrated solar thermal technologies through networking activities, collaboration with industry in joint research projects, licensing of innovations and know-how, and by spinning-off new start-ups. Since 2007, five spin-off firms have emerged from the institute, of which four are still commercially active as of 2019. We will continue to innovate in solar power, process heat and fuel production, through cooperation with the national CSP industry in particular.

Prof. Dr.-Ing.
Robert Pitz-Paal
Director

Prof. Dr.-Ing.
Bernhard Hoffschmidt
Director

Heliostat field of the Jüich Solar Tower.

Cooperation and Networking Highlights

The institute's overall understanding of CSP systems enables it to identify the complementary external research competencies needed to successfully develop CSP technology.

Cooperation with universities and other research centres

It identifies those universities and research institutions, both externally and within DLR that offer relevant expertise, and invites them to collaborate on specific projects. In the past, the institute has established two virtual institutes to strategically shape these collaborations. Those were the Virtual Institute for Central Receiver Power Plants – together with RWTH Aachen University, FH Aachen University of Applied Sciences and KU Leuven University (2008-2011) and the Virtual Institute Solar Syngas – together with TU Clausthal University of Technology, KIT Karlsruhe Institute of Technology and ETH Zurich University (2012-2017).

Joint professorships with Aachen University and Dresden University allow the Institute of Solar Research to offer instruction and supervision at the bachelors, masters and PhD-level of theses, empowering the institute to recruit and develop young talents.

Cooperation with industry

In 2013, the institute supported the establishment of the German Association for Concentrated Solar Power (DCSP) which includes one of the two directors of the Solar Institute on its board. In this way, it has been able to establish close R&D co-operation with member companies. This national CSP industry association now has 30 members. It's main task is to represent the German CSP industry's needs before policy-makers, to ensure that questions on research priorities are addressed and that German technology options are represented in international delegation travels and energy partnerships.

DCSP also has the mandate to coordinate with development banks and development aid organisations. It holds regular talks with parliamentarians and representatives of ministries, develops position papers and organises specialist events for its members. Due to our size and competences the institute is the natural partner with industry in national research projects, and has established close R&D co-operation with both member companies and international CSP firms.

Joint research with CIEMAT

DLR has a longstanding cooperation agreement with CIEMAT extending back to 1984. Then in 1998, a modification to the cooperation agreement has given DLR staff privileged access to use the facilities on the Plataforma Solar de Almería (PSA), and provides some DLR employees with a workplace there. Both organisations jointly operate test facilities and laboratories including the comprehensively equipped meteorological station (METAS), the laboratory for the analysis of reflective materials (OPAC), and the parabolic troughs rotating test platform (KONTAS).

In addition, other project-related large pilot plants can be used as testing facilities, typically in joint projects. DLR's Institute of Solar Research also maintains a separate office in the nearby town of Almería for organising any separate projects with Spanish partners independently of CIEMAT.

Networking with European research partners

The close cooperation between DLR and CIEMAT formed the basis for the establishment of the Alliance of European Laboratories for Research and Technology on Solar Concentrating Systems (SolLab) with the European research partners CNRS (France) and PSI/ETH (Switzerland).

This alliance, with the support of other EU projects and European partners, has provided access to research facilities for researchers and organised the exchange of scientists. SolLab has initiated a harmonisation of testing and measurement techniques in the facilities of the partners, and was the contact point for the European Commission's research programs. The Alliance has meanwhile integrated itself into the European Energy Research Alliance within the EERA-Joint Programme-CSP group. It continues to network internationally, encompassing all relevant European research partners.

DLR is also a member of the European Industrial Association ESTELA (European Solar Thermal Industry Alliance), which represents the interests of the solar thermal industry in Brussels before the European Commission. Institute staff participated in ESTELA's preparation of the European Solar Thermal Research Agenda adopted in 2012 and supported the EU's Solar Energy Technology Initiative (SET-Plan) in 2014.

Contributions to the International Energy Agency's collaboration programme SolarPACES

The institute acts as the German representative of this international network and is active in many coordinating functions, in particular in the function of secretary-general, and the chairman and in the coordination of several of its task groups within solar thermal technologies.

SolarPACES (Solar Power and Chemical Energy Systems) has contributed significantly to the visibility and dissemination of technology in recent years, notably through the annual organisation of the largest scientific conference in the field, the creation of potential technology, roadmaps for the technology and in the drafting of guidelines to determine the capabilities of specific components and systems.

The data on technology and market development are directly incorporated into higher-level energy studies and IEA forecasts. As part of this network, the institute has exchanged scientists and initiated numerous bilateral collaborations, in particular with partners in the USA and Australia.

Prof. Dr.-Ing.
Robert Pitz-Paal
Director

Prof. Dr.-Ing.
Bernhard Hoffschmidt
Director

Figure 1: The SolarPACES collaboration programme of the International Energy Agency IEA has 20 country members. Image: SolarPACES.

Public Relation Highlights

Public Relations has been a high priority from our beginning, with around 150 news items published since 2011. The Institute of Solar Research and DLR itself regularly reports news of our current research topics, tours by politicians and events and tours at our sites. For communication with political decision-makers, the institute also cultivates face-to-face meetings. Since 2011, numerous political representatives and energy transition stakeholders have visited the institute's test facilities to learn about DLR Solar Research and its contribution to the German and global energy transition.

The inauguration of new test facilities increased the institute's visibility

Figure 2: Sun-to-Liquid solar thermochemical research facility located at IMDEA Energy Institute Móstoles, Madrid, Spain. Picture: Christophe Ramage ©ARTTIC 2019.

Since 2011, the institute has commissioned a number of new test facilities and laboratories. At the opening of the larger facilities, the institute welcomed guests from politics, industrial partners and sponsors. Highlights were:

- On March 5, 2013, North Rhine-Westphalia (NRW) Science Minister Svenja Schulze opened the Competence Center for Ceramic Materials and Thermal Storage Technologies in Energy Research (CeraStorE). Scientists from the DLR Institutes of Materials Research, Engineering Thermodynamics and Solar Research find this an ideal setting to work in an intradisciplinary manner.
- In the first Quarter of 2017, Synlight® at Jülich, the world's largest solar simulator, was DLR's most featured media topic. With 547 articles published, Synlight® has also had the second highest result of all quarters analysed so far. Project Leader Kai Wieghardt, Director of the Institute of Solar Research Bernhard Hoffschmidt, and DLR's Board Member for Energy and Traffic, Karsten Lemmer, were the most cited members of the DLR staff during the first quarter of 2017 (Figure 1).
- The Institute of Solar Research was part of the Sun-to-Liquid project, which succeeded in producing solar jet fuel from sunlight, water and CO_2 in a solar thermal installation, in June 2019 for the first time ever. Project partners generated news excitement and raised global awareness of this renewable energy breakthrough. In the following weeks Christian Sattler and Martin Roeb from the Institute of Solar Research were sought after interview partners by the German media (Figure 2).
- In 2019 the construction of the Jülich Multifocal Tower began. Two energy policy-makers attended the official ceremony: Secretary of state Andreas Feicht from the Federal Ministry of Economics and Energy and Andreas Pinkwart, Minister of Economics, Innovation, Digitalisation and Energy of the federal state North Rhine-Westphalia (Figure 3).

Figure 1: The inauguration of Synlight® in 2017 created high public awareness worldwide.

Great public interest in the institute's large-scale research facilities in Cologne and Jülich

Figure 3: NRW Minister Pinkwart, DLR's Board Member Lemmer and Federal Secretary of State Feicht in Jülich (f.l.t.r.).

The solar furnace at the Cologne site has been a very popular destination since its opening 25 years ago, toured by policy-makers, research organisations and the general public. Just between 2011 and 2019 this amounted to 7,000 visits. A sintering process for building blocks made of a dust like lunar dust, developed and tested in the Cologne solar furnace, has been just one of the topics featured in print media and on television in 2019.

In 2011 the government of North Rhine-Westphalia recognised the research at DLR's Jülich Solar Tower, awarding it as a Site of Innovation (in German: Ort des Fortschritts). NRW Minister Svenja Schulze presented the award which is mounted next to the entrance of the tower. The institute receives many requests to visit the Jülich Solar Tower. In 2017 the Jülich site participated in the Climate Days NRW event, opening its doors to the general public (Figure 4).

However, the Jülich site was still lacking the space and staff to receive and inform groups from the general public on a regular basis. Therefore, the institute initiated the construction of a visitor center close to the Solar Tower. Beginning in spring of 2020, trained guides will inform interested guests about DLR's Solar Research.

Figure 4: During the Climate Days NRW the Jülich Solar Tower opened its gates to the general public. Picture: EnergieAgentur.NRW.

Germany's largest scientific colloquium on concentrating solar technologies: Kölner Sonnenkolloquium

For over 20 years, this event has been the largest German-speaking conference for solar thermal power plant technologies. It brings together and educates researchers and professionals from related industries as well as representatives from the world of climate and clean energy policy, both policy-makers and funding bodies. With more than 100 participants each year the colloquium is a valuable forum for stimulating discussions and networking.

Supplying accurate information on topics related to the global energy transition

As part of the global energy transition, the Institute of Solar Research has competent spokespersons with in-depth scientific knowledge in energy technologies to answer media requests. The topics of solar fuels, solar industrial process heat and heat storage power plants now attract significant media attention. The Institute of Solar Research contributes to the public discourse on the energy transition with informed interview statements and press news about its research projects.

Elke Reuschenbach
Public Relations

Research Highlights

Advanced Systems Design and Testing

Seamless Flow – Solar Steam Generation in Line Focus Systems

The Institute of Solar Research has helped in the development of the direct solar steam generation in parabolic troughs from the beginning in close co-operation with CIEMAT in Spain. One achievement of this work is the Direct Solar Steam (DISS) test loop at Plataforma Solar de Almería (PSA), commissioned in 1999. Our modelling and experimental experience has helped in the development of a number of process heat plants over the last decade using direct solar steam.

The validation of thermo-fluid dynamic models and the operating experience gained with the DISS test facility paved the way for two commercial direct steam generation plants which started production in 2012: TSE1 in Thailand and PE2 in Spain. Both employ the robust conventional recirculation process, where a steam drum at the end of the evaporator section separates liquid water from dry saturated steam. We were closely involved in their development and commissioning.

Once-through operation understood and demonstrated

An alternative to recirculation, the once-through process would enable significant simplifications in solar field layout with associated cost reductions. Control system development and demonstration was needed to prove the concept. To do this we extended the DISS loop at PSA (Figure 1) to 1,000 metres to prove our proprietary control concept using two water injections along the loop. As in conventional recirculation boilers, the liquid water entering the collector loop is pre-heated, evaporated, and finally superheated. Particular challenges for the solar boiler arise from changes in irradiation with passing clouds, which lead to rapid axial shift of the dry-out point position. Any local shift of this end point of evaporation can cause temperature gradients in the pipe walls as the temperature of the fluid at this position can change from evaporation temperature to superheated conditions.

The first water injection at 600 metres controls the position of the evaporation end point. The second water injection is located before the last collector to control the final steam outlet temperature. Our extended dynamic models are able to simulate such processes in detail and show good conformity with measurements. Figure 2 shows measured and simulated temperatures at the loop inlet, at the 850 metre point, and at the loop outlet, resulting from different disturbances acting on the loop.

Temperature variations can be kept within safe limits

A critical aspect of direct steam generation is the temperature difference over the cross-sections of the pipes induced by different wetting angles of the fluid. We have designed and built special absorber tubes with six temperature sensors arranged over the circumference (Figure 3). Figure 4 shows an example of measured temperatures at the 609 metre mark. In this example, the endpoint of evaporation moves towards the inlet of the loop. The cross-section wetted at the bottom transitions into fully superheated at about 4:06 pm. Temperature sensors C, D, and E located in the lower half of the pipe indicate a fluctuation in the pipe wetting at these positions. Once the location of a sensor is wetted, the temperature falls; once it becomes dry, the temperature rises.

The resulting temperature differences over the pipe circumference induced by the natural fluctuations are well below 50 Kelvin which is considered a critical value for the absorber pipes. During the superheated phase, the temperature fluctuations disappear since the whole pipe becomes dry. Overall temperature rises with maximum temperature differences rising. The temperature difference now is induced by the solar heating which comes from one side of the pipe (direction of sensor D) and causes a temperature gradient over the cross-section. However, the value is well below critical limits. Our latest research indicates that model predictive control approaches offer new possibilities in further stabilising the process. A key element is very-short term forecasting of spatially resolved irradiance over the solar field, which is made available using the DLR-developed all-sky imager (See pp. 38-391: "Staring at the Sun – Solar Radiation Nowcasting for Enhanced Plant Operation").

Figure 1: DISS test loop at PSA upgraded to once-through operation at 120 bar/500°C.

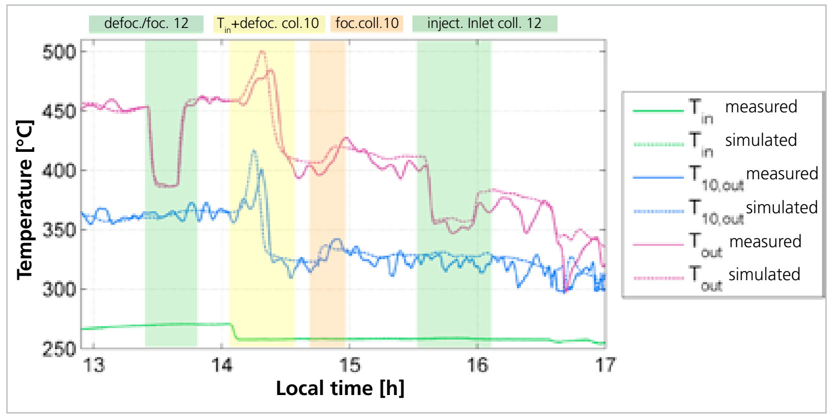


Figure 2: Measured and simulated temperature at three positions along the collector loop.

Current research and outlook

Our research results at the Institute of Solar Research have shown that the once-through process can be controlled. This provides a new alternative to the recirculation process for future plants with direct steam generation technology, at potentially lower cost. However, one ongoing challenge is storage. Some industries requiring steam have round-the-clock needs, but cost-efficient storage technology for direct solar steam generation is still under development. For now, this need is being met by including heat from a biomass boiler (or a fossil-fueled boiler), with direct steam generation from the solar field proposed as renewable contribution to overall energy demand. Current research is focused on monitoring and improving these hybrid processes to enable unsupervised operation, especially of small plants.

Figure 3: DLR measurement receiver with six temperature sensors on circumference (see A - F in Figure 4) and one sensor in the fluid.

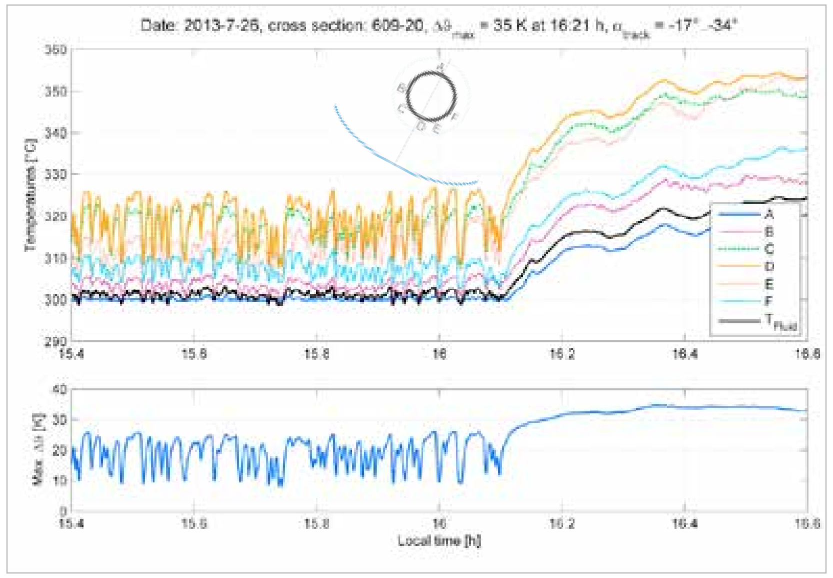
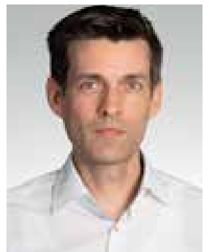


Figure 4: Measured temperatures (top) and maximum temperature difference (bottom) in cross-section of collector 9.



Dr.-Ing. Tobias Hirsch
Team Leader

Rolling Stones – Direct Absorption Particle Receiver Technology

Two main objectives of CSP research are further cost reduction and dispatchable power supply through integration of thermal storage. Researchers are investigating solid, sand-like ceramic particles as heat transfer and storage medium because they have the potential to meet these objectives. Such particles can be heated up to 1,000°C, enabling higher operation temperatures for various process heat applications and power cycles with increased efficiencies.

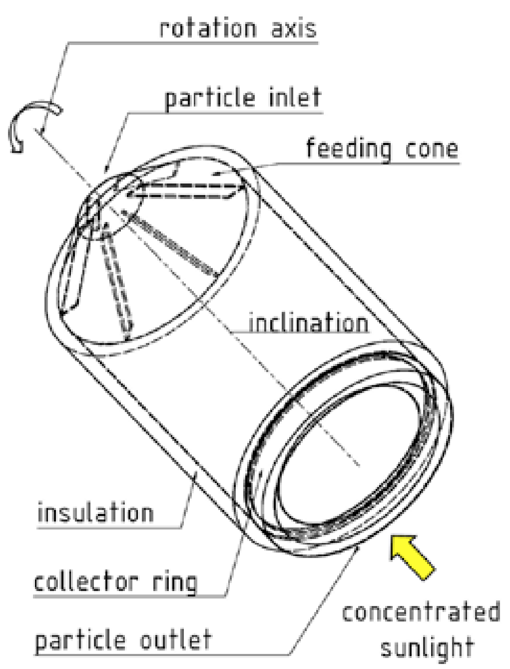


Figure 1: Scheme of centrifugal particle receiver CentRec®.

Compared to state-of-the-art molten salt systems, particle systems can have a storage density at least twice as high, which reduces costs for storing the heat. Unlike molten salt, particles withstand higher temperatures and do not freeze at low temperature. Therefore, they do not need heat tracing and complex operation modes.

We use particles made of sintered bauxite with a diameter between 0.1 and 1.3 mm. Their dark color makes them suitable for direct absorption of solar radiation. This is cheaper than indirect absorption where the heat transfer medium flows through directly irradiated pipes, made of expensive metal alloys. Direct absorption also allows high solar flux densities at high operating temperatures, necessary to obtain thermal receiver efficiencies of above 90 percent.

Centrifugal Particle Receiver CentRec®

DLR developed a centrifugal particle receiver technology, CentRec®, as one of our direct absorption concepts. The CentRec® receiver (Figure 1) consists of a rotating drum with an inclined rotation axis and an open aperture oriented towards the heliostat field. Particles enter at the top of the drum and move along the inner surface forming a thin, optically dense particle film driven by centrifugal and gravitational forces. While moving down, particles are heated up by direct absorption and leave the receiver at the lower end of the drum. Afterwards, they are collected in storage.

Rotational speed of the receiver is controlled in a way that the interaction between centrifugal and gravitational forces allows for adjusting the residence time of the particles in the receiver: the lower the speed, the higher the share of gravitational force and the shorter the time particles are exposed to solar radiation. This unique receiver property enables the formation of a dense particle film under all load conditions and allows accurate control of the receiver outlet temperature.

Figure 2: CentRec® Receiver prototype during on-sun operation in DLR's Jülich Solar Tower.

Development and tests of prototypes

Initially, prototype tests of CentRec® were conducted in 2013 at about 10 kW_{th}. During these proof-of-concept tests, a receiver outlet temperature of 900°C was successfully demonstrated in the solar simulator at DLR Cologne.

Then, between 2015 and 2017 we developed, manufactured and integrated into DLR's experimental solar power plant in Jülich, a pre-commercial prototype of 2.5 MW_{th} (Figure 2), with a particle storage and transport system. The plant was operated for 125 hours, with nearly 70 hours of that on-sun, and had a very reliable operation with fast ramp-up. In this prototype, receiver design outlet temperature even exceeded expectations, reaching up to 965°C. The tests confirmed the main characteristics that we required in the CentRec® receiver technology: high receiver outlet temperatures, homogenous particle film behavior and a resulting homogenous temperature distribution over the circumference of the rotating receiver (Figure 3). In our high temperature testing we found no hot spots which might cause receiver damage or increase thermal losses.

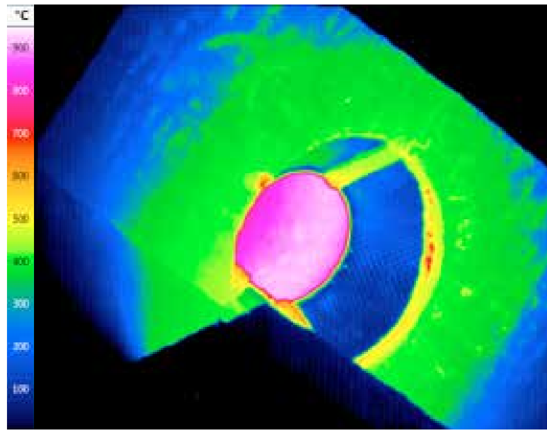


Figure 3: Infrared measurement of receiver aperture, demonstrating homogenous circumferential temperature distribution in the particle film.

Although only part load tests with solar input power up to 300 kW were realised, high receiver efficiencies of up to 90 percent for full load operation are expected based on results of a coupled ray-tracing and FEM model validated with measurement data (Figure 4).

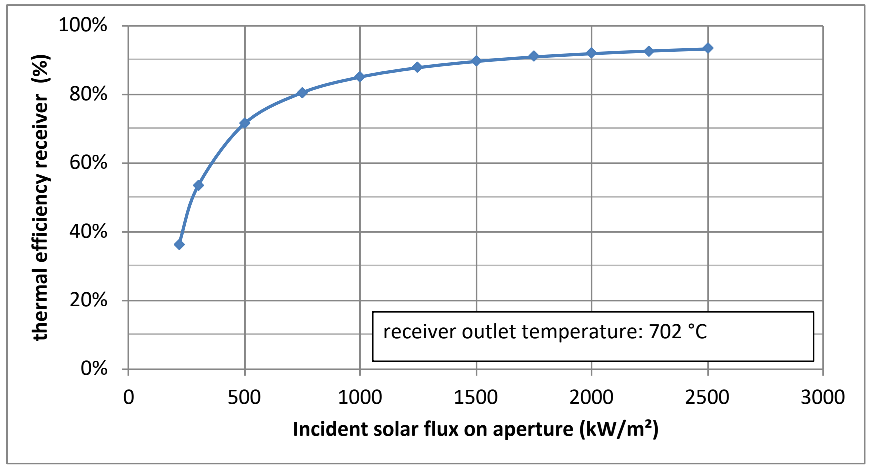


Figure 4: Expected efficiency for higher solar flux based on measurements at 200 kW/m².

In parallel, several particle related topics have been addressed. Experimental analysis of corrosion, attrition and erosion, further investigations of particle film characteristics and improvement of optical properties of particles have been carried out, and show us those areas where we can make future improvements. We are now developing a receiver for higher thermal power and other system components like the heat exchanger. Case studies for applications, particularly in process heat industries, have had promising results.

Exploitation of results

The centrifugal particle receiver technology was licensed to HelioHeat GmbH, a new DLR spin-off company in 2019. Test infrastructure for further development of components is under development and will be integrated into DLR's Multifocal Tower in Jülich. Together with 40 researchers from 13 countries working on solar particle systems, our particle research activities are part of the SolarPACES Particle Technology Working Group dedicated to international cooperation and knowledge exchange. Building on this research, several partners including DLR and HelioHeat founded a consortium in October 2019 to develop the first demonstration plant in Italy.

Dr.-Ing. Reiner Buck
Head of Department

Miriam Ebert
Project Manager

More than just Hot Air – Open Volumetric Receiver Technology

To really exploit the high efficiency potential of open volumetric receivers, a major task in their design is to ensure a high air return rate. With the patented HiTRec technology – a DLR development that started in the late nineties – the warm return air is blown out between the absorber modules over the entire receiver surface (Figure 1). However, with this design, air return rates of only 50-60 percent are possible. So a first step to improve air return was to get a better understanding of what happens with the flow in front of the absorbers.

Figure 1: Ceramic absorber modules in the HiTRec receiver support structure.

Flow field detection

Particle Image Velocimetry (PIV) was chosen as a quantitative 2D flow field detection method suitable for air flows. The most important criterion for selection of this complex measuring method was its applicability under real operating conditions. A single ceramic absorber module was positioned in a test rig and irradiated with our High-Flux Solar Simulator based on elliptical reflectors with xenon short-arc lamps. Air was sucked through the honeycomb absorber and heated up to 650°C while warm air of about 100°C was blown out along the edges of the square absorber module as in the real receiver situation (Figure 2).

For the quantitative measurement of velocity fields with PIV, the flow area to be investigated is loaded with titan dioxide particles that follow the flow as slip-free as possible. For the fluidization of the particles a fluidised bed is used, which is fed by a compressed air tank. A laser spans a plane through the flow area and the particles floating in the fluid scatter the laser light as it passes through the plane. Perpendicular to this plane, a camera system records the scattered light captured by the lens (Figure 4). As laser, an Nd:YAG solid state laser with pulse energies up to 200 mJ was used. For each snapshot of the velocity field, the laser sends two light pulses at a short time interval. The CCD camera is synchronised with the laser pulses and stores two frames of scattered light. The time interval between the pulses is set between 200 - 500 µs in order to determine the resulting particle shifts with a correlation method.

From the displacement vectors obtained through the image evaluation a two-dimensional velocity field is calculated which represents the quasi-instantaneous velocities of the turbulent flow. By averageing over a number of measurement times a mean velocity field can be determined (Figure 3). The results show that only part of the warm return air is diverted and sucked back in through the absorber. The momentum of the other part of the return air is too high, so that the intake of ambient air instead leads to a lower flow resistance. The non-deflected return air forms a turbulent loss jet which leaves the absorber front.

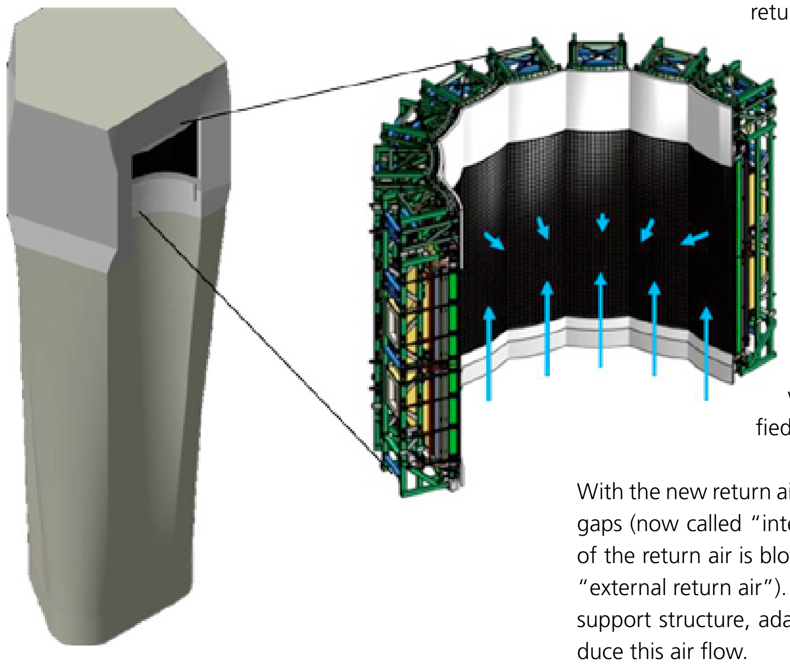


Figure 2: New cavity receiver design with internal and external air return.

Measures for improvement

The results of the measurement campaign were also used for the validation of a numerical model that was implemented in the open source CFD code OpenFOAM. This model allowed the analysis of operating points beyond those of the measurement campaign and supported the investigation of improvement measures. It could be shown that the return air ratio increases when just part of the warm air is blown out through the absorber gaps. When only 40 percent of the warm air is returned through the gaps, 100 percent will be sucked in again. This insight led to the development of a modified air return concept and a re-design of the receiver geometry.

With the new return air concept, the fraction of the return air blown out through the absorber gaps (now called "internal return air") can be reduced during operation. The other fraction of the return air is blown out parallel to the absorber surface from the receiver edges (called "external return air"). As the internal return air is used for the cooling of the metallic receiver support structure, adaptations of the internal construction were necessary to be able to reduce this air flow.

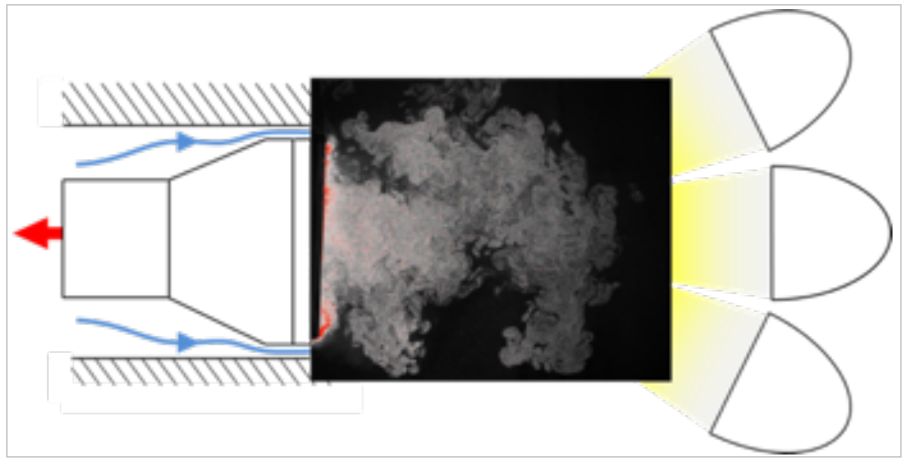
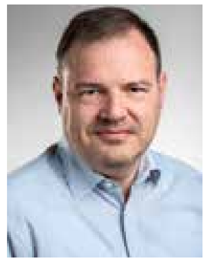


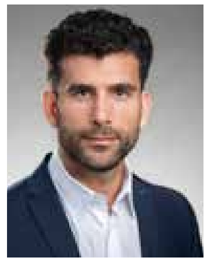
Figure 3: Principle test setup and single camera picture during the PIV measurement campaign.

The basic design concept of the HiTRec receiver technology was its strictly modular setup with repeated use of the same convex-shaped subunits for a small test panel up to a large fully cylindrical industrial scale receiver. The re-design tried to keep as much of the modularity as possible and to adopt the improvement measures for the return air. The result is a multi-cavity design where each receiver cavity is composed of convex curved segments (Figure 2). This allows the integration of air ducts for external air return from the edges of the cavity. Additionally, the influence of wind on the return air will be reduced.

A numerical model, validated at the Jülich Solar Tower, revealed great potential for the new cavity receiver design with external air return: The air return ratio is increased up to 85 percent and the thermal receiver efficiency can be up to 90 percent at 650°C air temperature. Also the system efficiency can be further improved because the external return air consumes less fan power.



Peter Schwarzbözl
Team Leader



Dr.-Ing. Daniel Maldonado Quinto
Project Manager

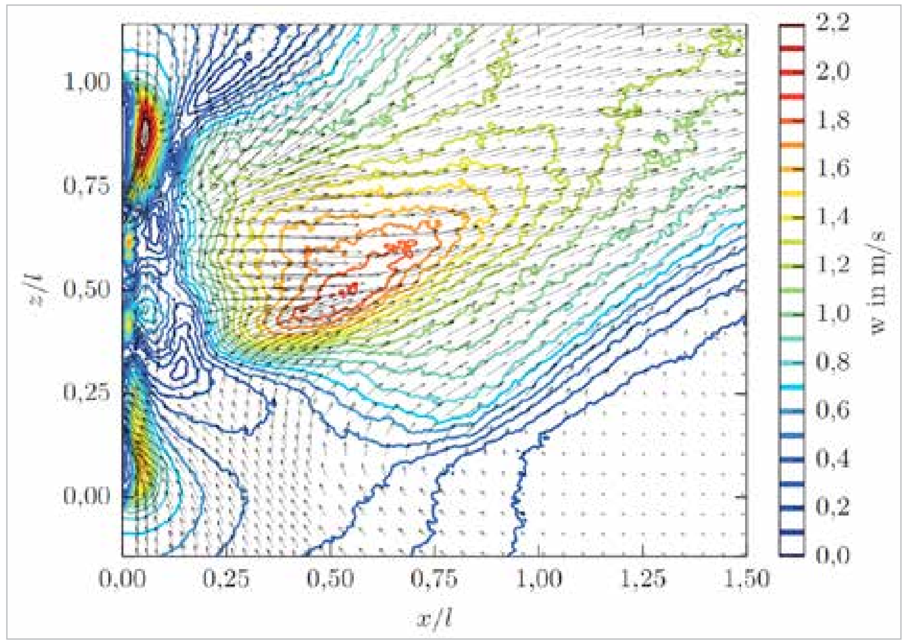


Figure 4: Flow field showing vectors and isolines of the mean air velocity in front of a single absorber.

A New Star?
Improved Receiver Concept for Molten Salt Towers

Concentrating solar power towers with molten salts for heat transfer and storage are able to reliably provide dispatchable renewable energy and could become the backbone of the future renewable energy supply. Although costs have come down, further cost reductions and efficiency improvements are needed to make it competitive with fossil-fueled power. To cut tower CSP costs, we work on heliostat aim point optimisation and have developed a novel receiver with the potential to reduce levelised cost of electricity compared to today's receivers.

Reducing optical losses in external central receivers

Currently, in external molten salt receivers the absorber panels are arranged cylindrically around an insulating and holding structure. Each panel comprises several parallel thin-walled tubes in which the molten salt is heated. The allowable flux density on each absorber tube is limited on one hand due to thermal stresses inside the tube caused by the one-sided irradiation and on the other hand due to an upper temperature limit for the molten salt to avoid rapid corrosion and salt degradation. So we can't exceed local flux densities at each individual heliostat aim point, yet at the same time we must maximise the integral irradiation power.

Conventional parameter-based aiming strategies lead to additional optical losses of more than 3.5 percent. We developed a metaheuristic aiming point optimisation procedure, derived from ant colony algorithms, and were able to reduce these additional optical losses below 1 percent, while taking into account local flux density limits. Applying this new aiming point optimisation procedure alone, we showed that the performance of an existing heliostat/receiver system can be maximised without any other design changes.

The economic viability of central receiver systems using tubular absorbers is very dependent on aperture area size. A large aperture is needed to minimise spillage losses, yet a small absorber surface increases receiver efficiency and minimises receiver costs. However, in conventional receivers, only one side of the absorber area, just half of it, can be used for direct heat transfer. This causes a large solar flux density gradient between the front and rear of the absorber tubes, inducing thermal stress that limits maximum permissible solar flux density.

A star-shaped solution

One design option to address these engineering challenges is to irradiate the panels from both sides. Our STAR receiver consists of multiple panels made of parallel tubes, welded to inlet and outlet headers at either end. Three outer pylons support a roof structure, from which the absorber panels are vertically hung. This permits unrestricted downward thermal expansion of the panels. Three absorber panel sections are arranged in a star-shaped fashion (Figure 1). This enables two-sided irradiation which doubles the heat flux density without exceeding total flux density limits. By limiting the number of extension sections to three, the decrease of aperture circumference compared to external receivers is minimised when the absorber area is kept constant.

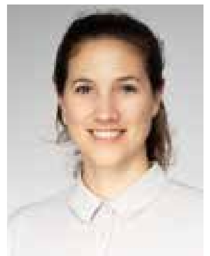
One of the main challenges of this novel concept is the relatively complex structural-mechanical design of the absorber panels. In contrast to conventional systems, the absorber tubes cannot be supported over the irradiated absorber height and thus have to withstand the wind loads occurring during operation, and the storm loads outside the operation, without additional support. Conventional panel designs would fail under these high wind loads.

So in the STAR receiver we group the absorber tubes in segments and arrange them in a staggered fashion. The absorber tubes of each segment are welded together, which stiffens the absorber panel. Our calculations indicate that with this segment-like arrangement of the absorber tubes, the maximum stresses occurring under storm loads at 280 km/h, can be reduced to well below the maximum permissible stresses.

A first numerical model of the STAR receiver has shown a thermal receiver efficiency about 1 percent higher than that of a comparable external receiver (Figure 2). Another finding was, that the LCOE can be reduced by up to 11 percent compared to state-of-the art external receivers.

Initially this design had low optical efficiencies because of a non-optimised aim point strategy. If all heliostats were to aim at the middle of the receiver, it would be subjected to extremely high flux densities (> 3 MW/m² at design point); well above the permissible limits.

So we revised our aim point optimisation procedure so as not to exceed local flux density limits, and showed that in the STAR receiver, a reduction of 38 percent in required absorber area can be achieved yet have lower spillage losses than an external receiver of the same thermal rating (Figure 2).



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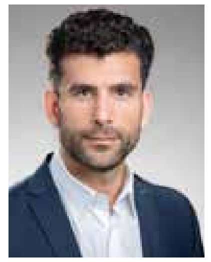

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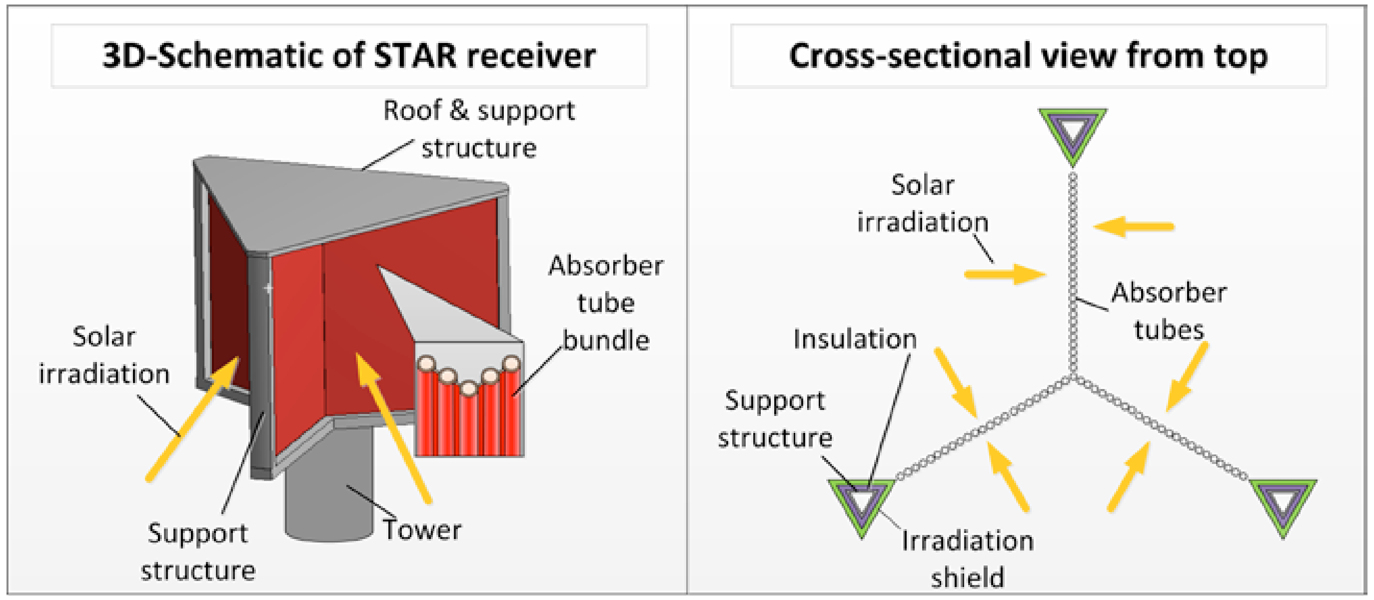


Figure 1: Schematic drawings of the STAR receiver concept.

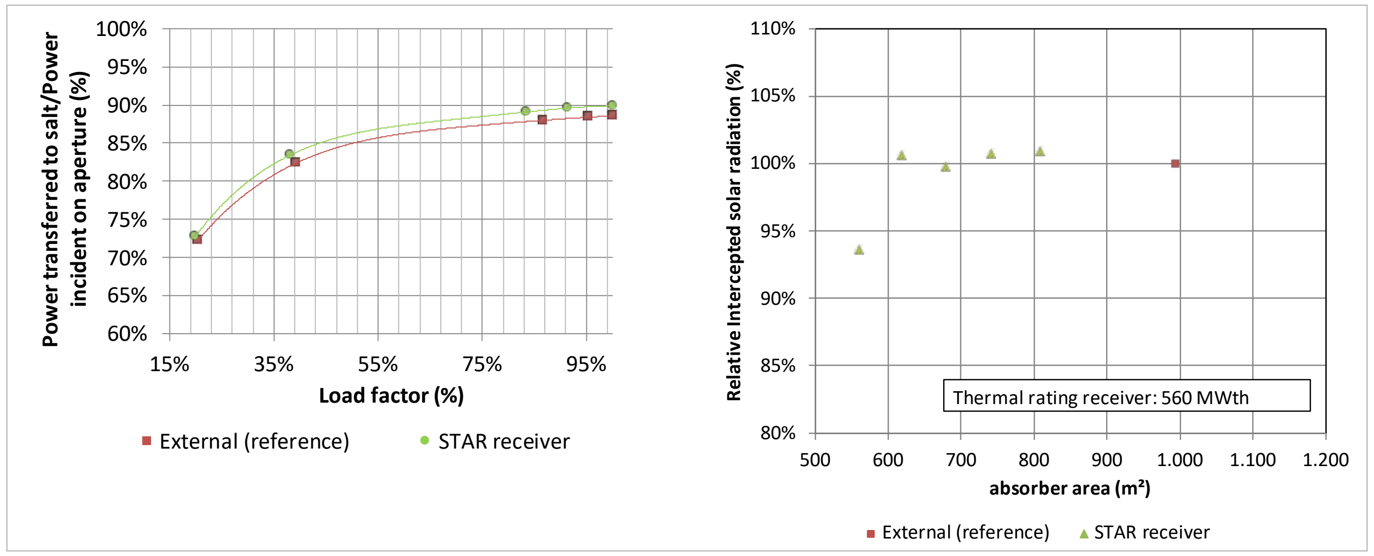


Figure 2: External VS STAR: efficiency as a function of load; Intercept as a function of built absorber area.

Less is More – Advanced Heliostats of Minimum Cost

To be competitive, the CSP industry must cut heliostat costs, as the solar field accounts for a significant percentage of plant costs. CSP firms must focus on existing solutions that are bankable in the short term. But also, for future plants, ground-breaking innovative heliostat designs must be found that meet this cost challenge. The Institute of Solar Research is working on such innovations, which may take several years of development time including building and testing prototypes. It is our aim to develop new solutions until they reach a readiness-level that enables their hand-over to the CSP industry.

We apply the experience and knowledge gained from our high-end heliostat measurement systems, ray-tracing tools, and wind load investigations to advance new heliostat designs, consult CSP industry, and to perform field acceptance tests of commercial tower plants.

Figure 1: 8 m² prototoype of low cost carousel heliostat with monolithic sandwich concentrator.

Innovative heliostat designs and subsystems

The institute has found and developed several promising heliostat concepts. One example is a patented carousel-type heliostat (Figure 1). Compared to the lowest cost heliostats on the market, we were able to cut costs by 20 percent (to below 80 €/m²) through a comprehensive set of innovations. These include a monolithic sandwich-cantilever-arm concentrator, a lay down of the concentrator during storms to reduce the wind loading, and a closed loop control to reduce the accuracy requirements on the mechanical components.

We also developed an automated cleaning system that demonstrably cut water consumption to just 5 percent of current systems. It is driven by the azimuth drive, which eliminates the need for its own actuator on each heliostat, cutting costs (Figure 3). Because of this very low operational cost and minimal water use, the carousel mirrors can be cleaned more often, for higher average operational efficiency in the heliostat field. So, while investment cost is similar to conventional cleaning systems, cost savings result from reduced operations cost and increased efficiency.

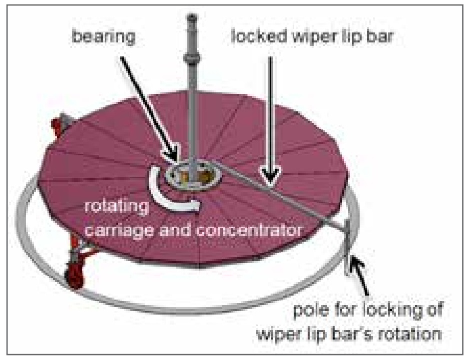


Figure 2: Automated heliostat wiper lip cleaning system for carousel heliostat.

An initial 8 m² heliostat prototype was built and tested successfully. Now, a further simplified and larger prototype is under development at 50 m².

Figure 3: Rim drive heliostat with 8 m² mirror surface for small solar tower plants and high local production share.

For small solar tower plants, small heliostats are better as they reduce astigmatism. For this purpose, an 8 m² rim drive heliostat has been developed (Figure 2). Due to the long lever arms of the rims, the loads on the drives are small and no high-precision mechanical components are needed. With no high-precision mechanical parts, this design results in cost reductions. Moreover, its simplicity facilitates to set up a local production site, permitting to meet local content rules and to produce at local costs.

Another innovation is a closed loop heliostat control system. A camera chip with fish eye optics is mounted on each heliostat and detects the positions of the centre points of the sun and of the receiver simultaneously. With this information the orientation of the concentrator can be calculated. The optical sensor can be a simple off-the-shelf smart phone camera chip with a small standard fish eye lens so it will not cost significantly more. First tests validated a sufficient repeatability of 0.2 mrad.

Wind loading, qualification, and consulting

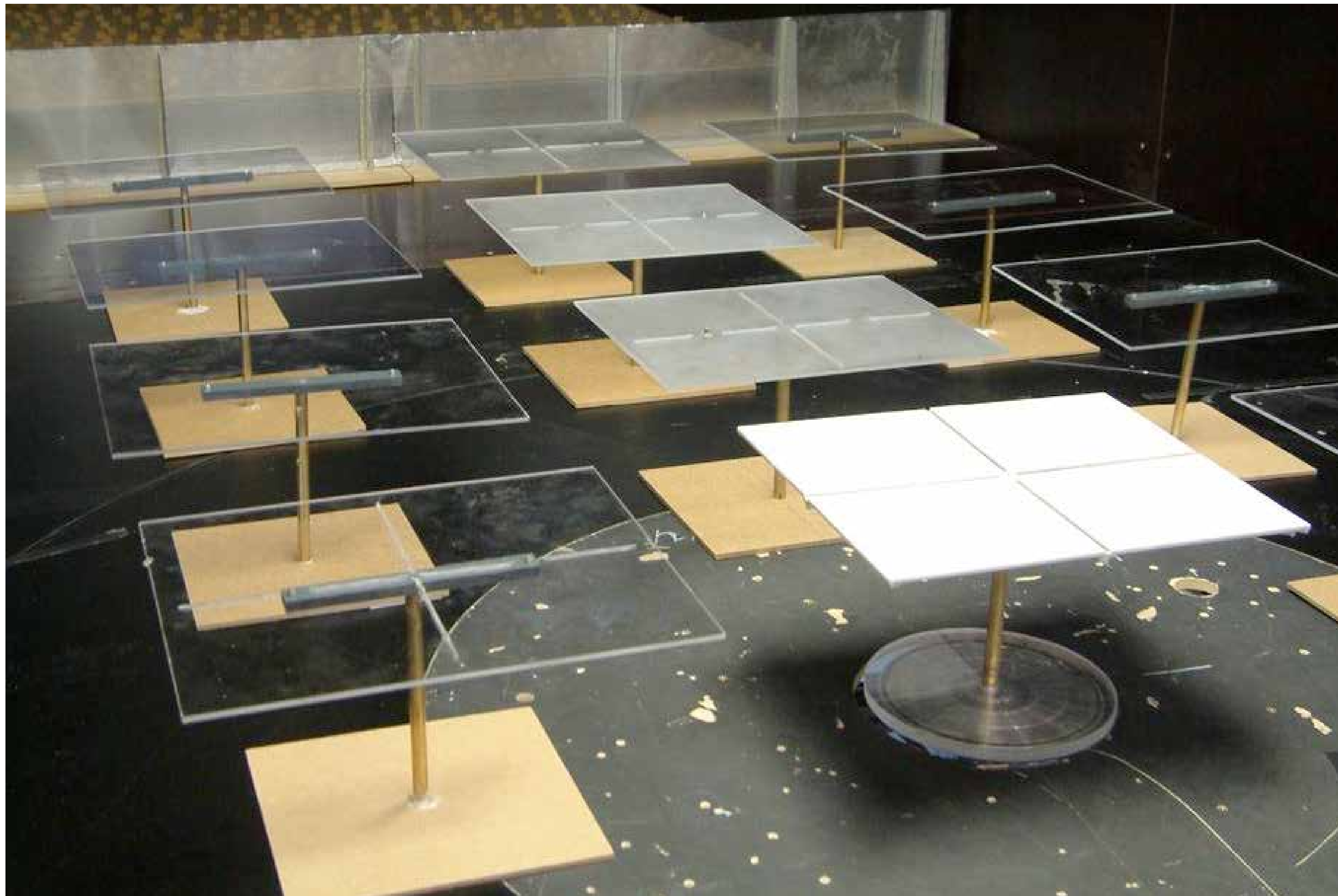
Wind is the main load on heliostats. Therefore, understanding wind loading is crucial for reliable and cost effective heliostat structure dimensioning. Many different impact factors on wind loading were investigated by wind tunnel tests and CFD simulations and the results published: aspect ratio and height of the concentrator, gaps between facets, Reynolds number, wind fences (Figure 4), heliostat field corners, vertical turbulence intensity, and gust duration, and dynamic wind loads.

For optical and tracking accuracy measurements, the institute has established an advanced heliostat test platform on the edge of the Jülich solar field (See pp. 70-71 "Jülich Solar Tower and Multifocal Tower"). The movement of heliostats caused by wind gusts can be measured with a dynamic photogrammetry system to determine dynamic wind loads. Special test rigs have been developed to investigate the long-term durability of single heliostat components like linear drives and chain gears over time. We can simulate lifetime durability of mirror and sandwich structures in our climate chambers and by outdoor tests.

The dimensioning of the heliostat structure is based on finite element calculations which use the results of both indoor wind tunnel and full scale outdoor tests. The impact of measured heliostat properties on annual energy yield is determined by heliostat field simulations using the institute's ray-tracing tools. Companies can confidently draw on our extensive heliostat expertise. Our experts were involved in the heliostat field acceptance tests of a large commercial solar tower plant. Our knowledge was also the basis for the most comprehensive review to date of heliostat development progress.

Dr.-Ing. Andreas Pfahl
Project Manager

Figure 4: Wind tunnel tests of wind fences. Picture: Wacker Ingenieure – Wind Engineering.



Good Bye Oil – Solar Production of Fuels and Commodities

Concentrated solar thermal (CST) radiation can provide the high temperatures needed to run thermochemical redox cycles or chemical reactions in solar reactors. There is a great potential for using such processes to obtain future fuels and commodities. Fuels can be gained from abundant feedstocks, like H_2O and CO_2, for example by synthesising renewable hydrogen from H_2O or by converting both H_2O and CO_2 to liquid hydrocarbons (Figure 1). Large CST plants even have the potential to supply liquid fuels at costs competitive with fossil fuels. Moreover, solar heat can be used in dedicated reactors to gain or transform commodities, for example to calcinate industrial cement raw meal or melt alloy scrap material).

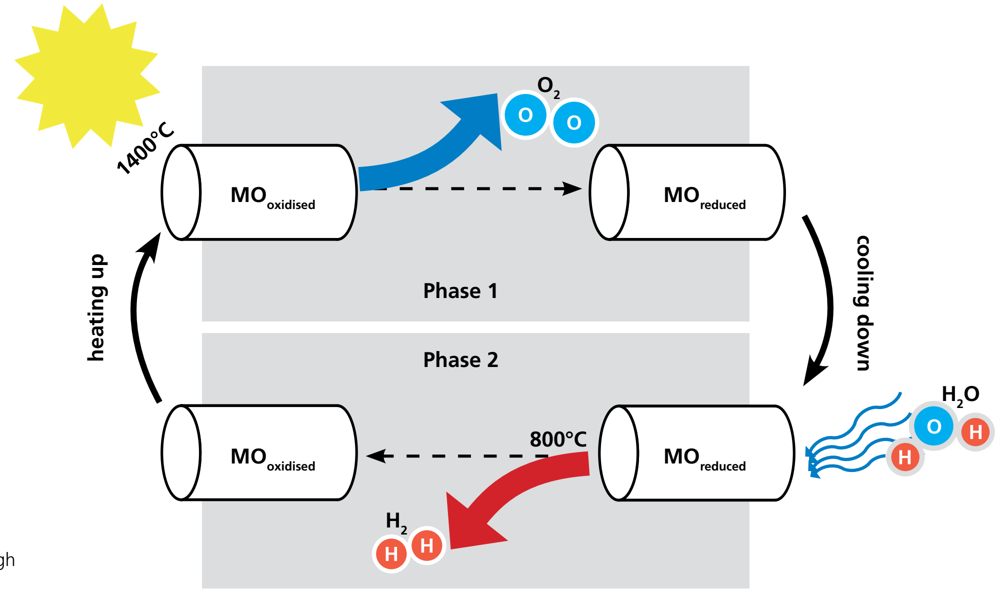


Figure 1: Scheme of a two-step solar thermo-chemical cycle for hydrogen production through water splitting.

Solar fuel production does not require arable land, enabling regional diversification. It does not compete with food production, adding renewable fuel options beyond biofuels. Adverse effects from direct or indirect land use change are very low in deserts. It can create economic benefits, enhance fuel supply security and generate jobs through replicability in a global market. DLR's estimate for Desertec that under one percent of global desert area could meet global power demands suggests that solar fuel production could scale.

Figure 2: Solar tower (left) at PSA hosting the 750 kW demonstration plant (right) for solar thermochemical hydrogen production. Picture left: DLR/Lannert.

Thermochemical hydrogen and synthesis gas from water and CO_2

Solar hydrogen has zero emissions. Solar fuels from CO_2 do release emissions when burned, but use CO_2 in their production, so unlike fossil fuels their impact is considered "Net Zero". Our research focuses on advanced solar concentration technology for high-flux/high-temperature fuel production. We built and tested a solar modular reactor technology for thermochemical hydrogen or syngas production at field scale. We develop and optimise high-performance redox materials and monolithic ceramic absorber structures with favorable thermodynamics, rapid kinetics, stable cyclic operation, and efficient heat and mass transfer. The technology is scalable through abundant feedstock and modular thermochemical reactor design. A two-step redox-cycle technology to split water into hydrogen and CO_2 into carbon monoxide is now being developed to field test level.

One of our European consortia investigated syngas production and a subsequent Fischer-Tropsch process to convert syngas further to kerosene at 50 kW scale. A second European consortium concentrates on the hydrogen generation for which we will now test three reactor modules operating in parallel on-sun at the 750 kW solar tower at Plataforma Solar de Almería (Figure 2), following our test of one of these reactors indoors at Synlight®, the world's largest artificial sun in Jülich.

We aim to show safe, reliable and efficient plant operation at temperatures up to 1400°C. A major part of our field scale testing will be automated plant control, which will be required in commercial plants.

Figure 3: Rotary kiln in the HFSS.

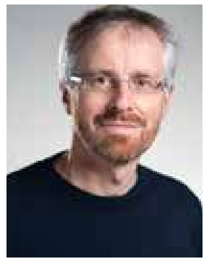
Solar thermal production of commodities using particle technologies

For the first time ever, DLR researchers have calcinated industrial cement raw meal with solar energy. We performed tests at our High-Flux Solar Simulator (HFSS) in a rotary kiln (Figure 3). With an input power of 14 kW we were able to treat flows between 4 and 12 kg/h and calcination ranged from 24 to 99 percent. We achieved total efficiencies between 19 and 40 percent. The highly calcined products had industrial quality, but we will need to optimise the reactor to achieve high calcination degrees and efficiencies consistently. The key parameter is the heat uptake of the cohesive powder, which is mainly determined by its mixing. For this purpose, the heat transfer to the bed is analysed for different cases in which mixing is induced with built-ins. The increase in heat uptake will be quantified to allow for improved reactor performance and to support the definition of routes for up-scaling.

These results extend our applications to the solar calcination of limestone-containing raw materials – a high temperature endothermal step. The handling of fine particles in the form of powders in solar research, which is required for this application, has so far been limited. However, it is necessary to continue this approach, since such materials are used in industry and cement making is one of the largest with a significant carbon footprint when powered conventionally by fossil fuels.

Another advantage of particle-based technologies for industrial solar chemical processes is their similarity to already established commercial technologies. A straightforward way to couple particle technologies to thermal storage makes it possible to have continuous operation, and the option to separate operational units makes it possible to optimise each individually.

However, particle-based approaches require new types of receiver/reactors for these processes with several key innovations. For some applications we form and optimise the active material into particles for easy transport, heat recovery, and continuous operation. For others the solar technology has to be adapted to the properties of available established feeds. The particles are directly irradiated in a moving bed which could be in a falling film or fluidised bed but our choice was using rotary kilns or moving the particle bed by conveyor systems like a slip-stick plate.



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Research Highlights

Modelling and Simulation

One Model Fits All? Simulation Tools for Solar Power Plants

To understand the function, the economic evaluation, and the optimisation of complete CSP systems, computer modelling is essential. Models deliver electricity yield and financial revenue calculations, the most important data for evaluating entire plants and technical improvements. This data is indispensable, as it is the key to project financing and market introduction.

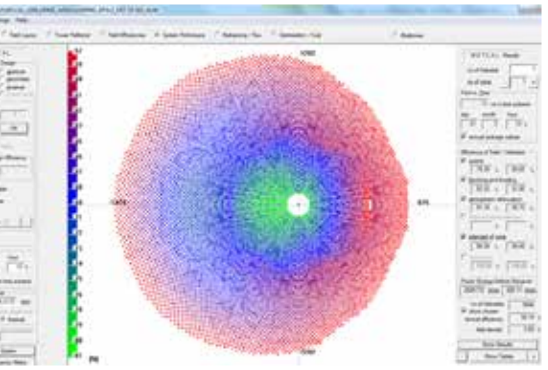

Figure 1: Example of a heliostat field layout and optimisation of a central receiver system with Visual HFLCAL.

Our main focus is on complete systems, comprising the solar field, receiver, heat transfer medium, storage, power block, and operations and maintenance strategies. But single components are also evaluated with respect to their impact on the complete system. Typical targets of our models are to:

- optimise the optical and thermal performance of solar towers and line focusing systems
- develop models and tools for calculating annual electricity yields in different types of power plants
- make comparative studies of different technologies as well as economic and ecological evaluations
- identify the most important factors concerning efficiency and costs for power plants and to develop innovative solutions
- develop and analyse combined CSP systems, for example Concentrated Solar Power + Heat for cooling, heating and desalination
- integrate other types of renewable energies with CSP systems, e.g. CSP-PV hybrid plants.

For this we develop software for the design of single components as well as for entire systems, and provide tools for the techno-economic assessment of these CSP systems.

DLR simulation tools for all levels of CSP simulation

Today there is a common understanding that design, performance evaluation and optimisation of solar thermal power plants should be based on annual simulation and yield assessment with hourly or even smaller temporal resolution. We are developing and maintaining a variety of models for this purpose. These models range from design tools for solar field or receiver layout to annual yield models for complete solar power plants.

Depending on the actual problem, the best suited available software must be chosen since there is often a conflict between limited simulation time and level of detail. We generally take a mixed approach, combining both commercially available tools as well as our own software we have developed. This enables flexible and fast solutions since commercial software helps avoid "reinventing the wheel" but often does not provide the flexibility and adaptability required for research.

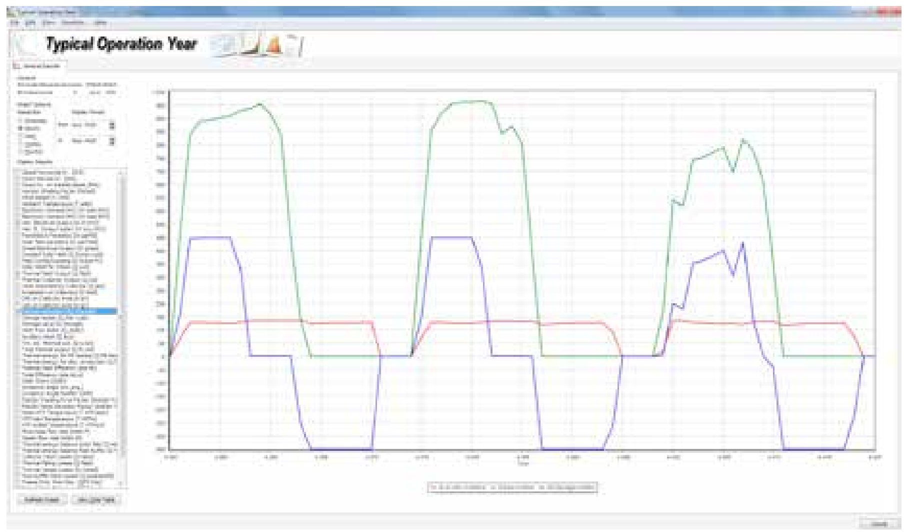

Figure 2: Visualisation of greenius results for three days showing the operation of a parabolic trough CSP plant.

We have developed special software tools like:

- Visual HFLCAL: for layout and optimisation of central receiver systems (Figure 1)
- STRAL®: ray-tracing laboratory for solar tower systems
- Virtual Solar Field: detailed and fast dynamic model representing line focusing solar fields
- greenius: for fast and easy annual performance simulation of renewable energy plants with emphasis on concentrating solar power plants (Figure 2).

For thermodynamic cycle calculation we are typically using the commercial software EBSILON® Professional (Figure 3). Since 2011 it has offered a library for solar power plant components (EbsSolar). The institute was involved in the implementation of this solar library by providing fundamental models and concepts and today EBSILON® Professional offers the opportunity to simulate CSP plants for all users. We validate these tools by using data from our experimental facilities or from commercial plants.

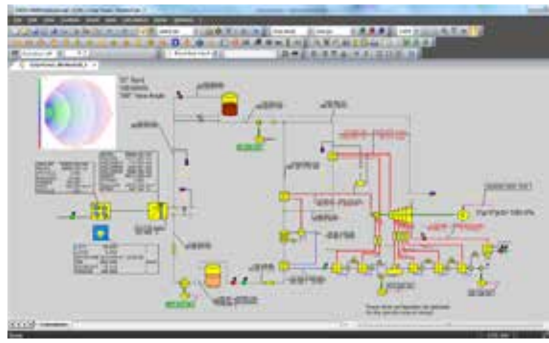

Figure 3: Example for a simulation model of a solar tower with EBSILON® Professional and the EbsSolar library for CSP modelling.

Improving CSP systems and accelerating their market introduction

We use our models to evaluate new heat transfer fluids, advanced thermal storage concepts, hybrid power plants and other questions which need a holistic approach in order to assess the system. Furthermore the performance models provide a basis for research, for instance on optimisation of dispatch, cleaning, or degradation. The big question is often: What is the impact of these improvement measures or degradation phenomena on annual yield or revenues?

We utilise our models to perform due diligence studies ordered by industry partners and financial institutions. They have great confidence in the expertise and long term experience of our institute and ask for support when an independent evaluation is needed.

On behalf of national and international organisations we have performed several studies of technologically driven cost reduction for solar thermal power plants.

These studies were not based on simple learning rate approaches but rather took into consideration the performance and cost impact of technical component improvements (Figure 4).

The institute also played an important role in the initiative to compile and publish the SolarPACES Guideline for Bankable STE Yield Assessment. We prepared the draft document together with German industry and research partners that was then finalised with international partners within the framework of SolarPACES.

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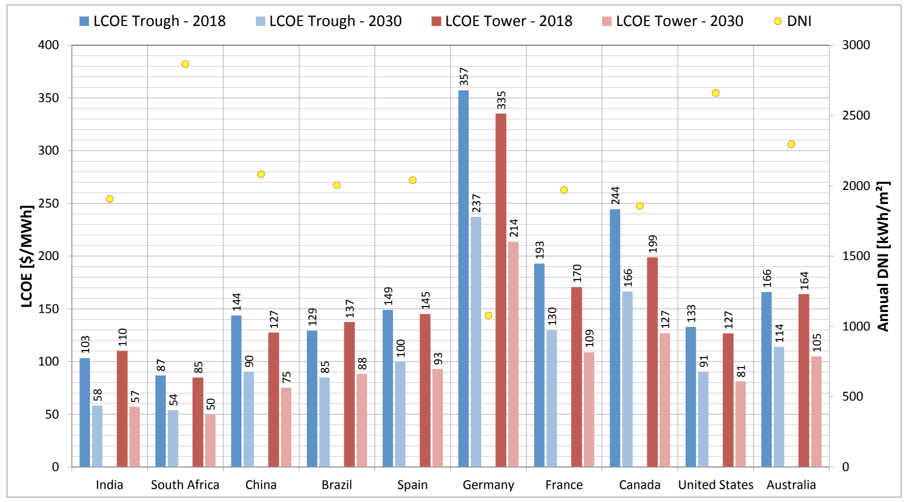


Figure 4: DNI resource and calculated LCOE for CSP plants in selected G20 countries considering local content and costs.

Running along the Edge – Simulation and Control of Molten Salt Tower Systems

Solar tower with molten salt as heat transfer fluid (HTF) is the preferred technology for new CSP plants because of its high thermal efficiency and simple and cost-effective storage. To reach highest efficiencies, the receiver system – a tubular receiver of cylindrical shape – has to be operated near the edge of its thermal load limits. Effective control of this component under transient conditions is therefore vital and dynamic simulation becomes essential to support this task.

The molten salt, typically a sodium nitrate/potassium nitrate mix, has to be operated inside the "temperature window" of its liquid state. Its design temperature range is 290°C to 565°C, while continuous operation limits are bulk temperatures of 260°C at the inlet and 580°C at the receiver outlet. The upper limit of the salt allowed for short term dynamic operation is about 600°C bulk or 615°C film temperature (usually reached at the inside of the receiver tubes near the outlet). A further limit is set by the maximum stress of the receiver tubes caused by uneven irradiation across the tubes' perimeters.

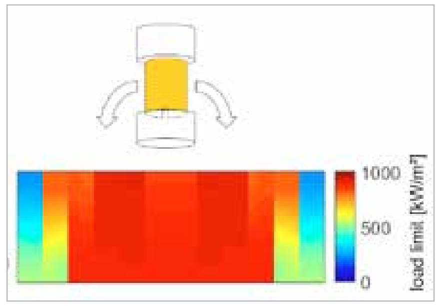


Figure 1: The load limit for a molten salt receiver on the unfolding of the receiver surface.

Both limitations, local film temperature of the salt and thermo-mechanical stress of the tubes, depend strongly on bulk salt temperature and salt mass flow (expressed as local load limits: Figure 1).The receiver's salt temperature and solar flux density must be carefully controlled to avoid these limits. In the pioneering demo plant Solar Two, the salt temperature was controlled by a combined PID controller. A feedback signal from the bulk salt temperature at receiver outlet was combined with the feed-forward signal from the flux on the receiver to manipulate the salt mass flow. The flux distribution was controlled with a model-based aim point control system.

The question we were looking to answer was whether the state-of-the-art control system from Solar Two can ensure safe and efficient operation of molten salt receivers during highly dynamic boundary conditions, or whether more elaborate control measures are needed.

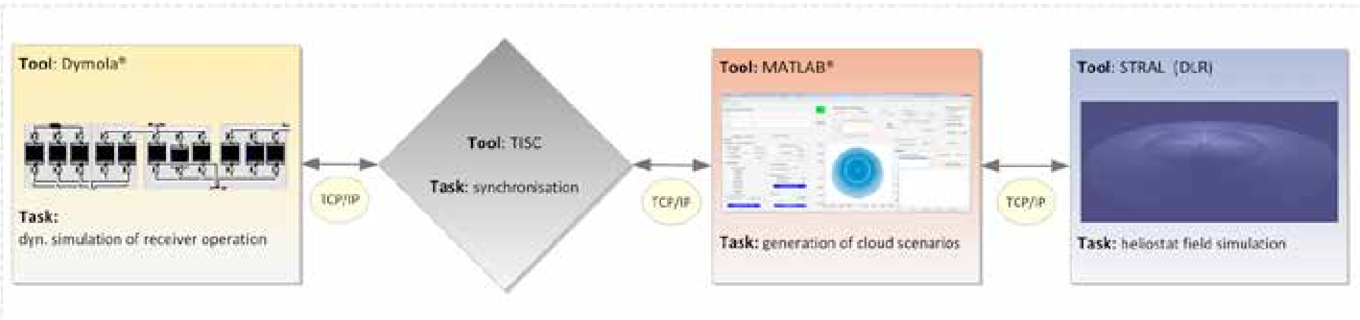
Tool coupling

To assess the plant behavior and the control system effectiveness, we modelled the heliostat field, receiver, molten salt circuit and control system, in a dynamic simulation setup. The DLR ray-tracing software STRAL was used to model the heliostat field, Dymola/Modellica for the molten salt receiver, peripherals and control system.

Our intention was to analyse the highly dynamic operation conditions at startup and shutdown and during cloud passages. So the molten salt receiver is modelled with a two-phase flow of salt and air. A cloud scenario manager was developed and implemented in MATLAB allowing the generation of random cloud passages with certain parameters, like cloud size, shape, speed, direction and coverage ratio. Alternatively, measured cloud scenarios recorded with our cloud detection system WobaS can be loaded.

The single simulation tools STRAL, MATLAB and Dymola were coupled via TCP/IP interfaces to form a distributed co-simulation setup (Figure 2).

Figure 2: Tool-coupling for co-simulation of a molten salt central receiver system.



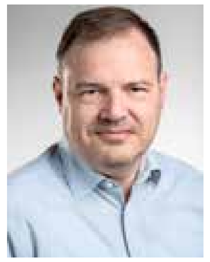
Cloud effects

We analysed a large number of cloud scenarios using this simulation setup. We found that there are various situations – caused by cloud passages – where the temperature limits will be violated when using the state-of-the-art Solar Two control system. These cloud effects can be divided into three categories.

- **"Static Effect":** When the heliostat field on the hemisphere of the receiver inlet is partly shaded, less flux is absorbed and the receiver control unit automatically reduces the mass flow to maintain the desired outlet temperature. Then, the film temperature near the receiver outlet can violate its upper limit, as this part of the receiver is still fully irradiated.
- **"Dynamic Effect":** When a cloud starts shading the heliostat field on the hemisphere of the receiver inlet, the feed-forward controller acts directly and reduces the mass flow. In this situation, the hot salt inside the receiver still propagates along its flow path in the fully irradiated part of the receiver and both the film and the bulk temperature will violate their limits (Figure 3).
- **"Sequential Re-Radiation":** When a small cloud shadow passes over the heliostat field in the direction of the salt flow path, the total mass flow is reduced to maintain the outlet temperature. The salt entering the receiver after the shadow has just passed this location will receive full irradiation on its path through the receiver leading to violation of the maximum bulk temperature as it is flowing at reduced mass flow.

The results also show that local defocusing of heliostats will not always be a good measure to cope with these effects, but will eventually worsen the problem.

This means that we do need to improve the state-of-the-art control system. So together with control experts from RWTH Aachen University, we are developing an advanced control system with a model predictive controller (MPC) that includes local DNI-Nowcasting data from the WobaS system. With this new control system we expect molten salt receivers could be operated more safely, but also more efficiently near the edge of their limits.



Peter Schwarzbözl
Team Leader

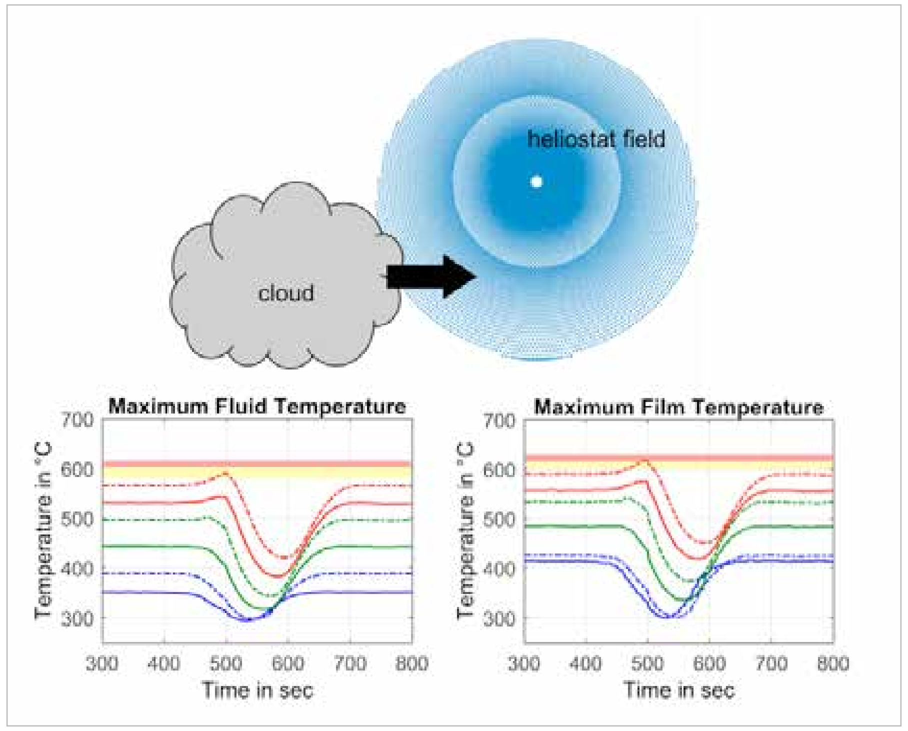


Figure 3: Example for the dynamic effect when a cloud shadow passes over the heliostat field on the receiver inlet side.

Solarised Fuel – Modelling of Solar Thermochemical Fuel Generation

The development of key components necessary to use concentrated solar thermal energy for fuel and chemical commodity production requires powerful modelling tools. Starting with lab experiments we need to be able to predict suitable ways to design and scale-up components. We need to know the potential performance and the techno-economic potential of a process in an early stage of development to best steer further development steps, so we need suitable numerical modeling tools.

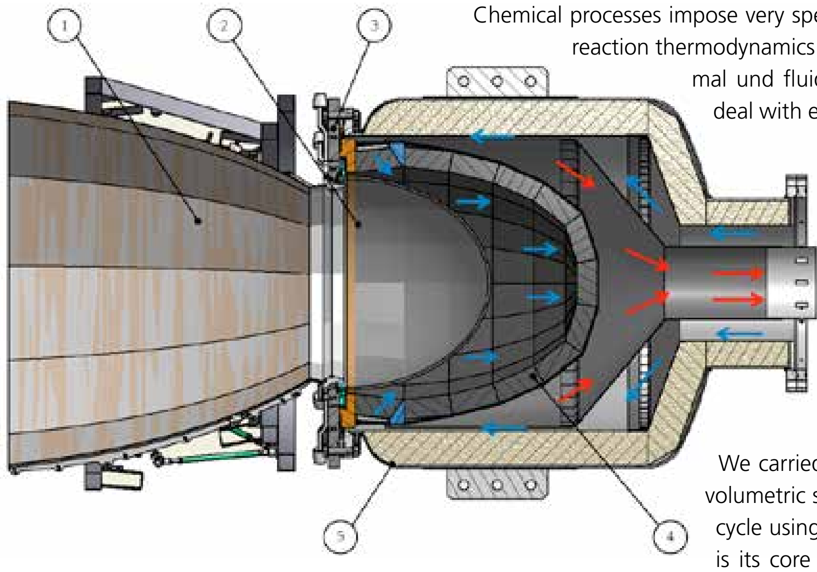


Figure 1: Schematic illustration of a solar receiver reactor for water splitting. (1) Secondary concentrator, (2) Quartz window, (3) Water cooled window flange (4) Porous ceria absorber, (5) Insulation.

Chemical processes impose very specific boundary conditions on such modelling tasks since reaction thermodynamics and kinetics have complex interactions with optical, thermal und fluid dynamic effects. On the component side we typically deal with either volumetric receiver technology based on porous absorbers (usually ceramic) or we apply a particle-based technology, as the heat transfer medium or as one of the reactants themselves. On the process side we must identify and optimise the parameters crucial for high efficiencies and smart process control, for example heat recovery and pump efficiencies.

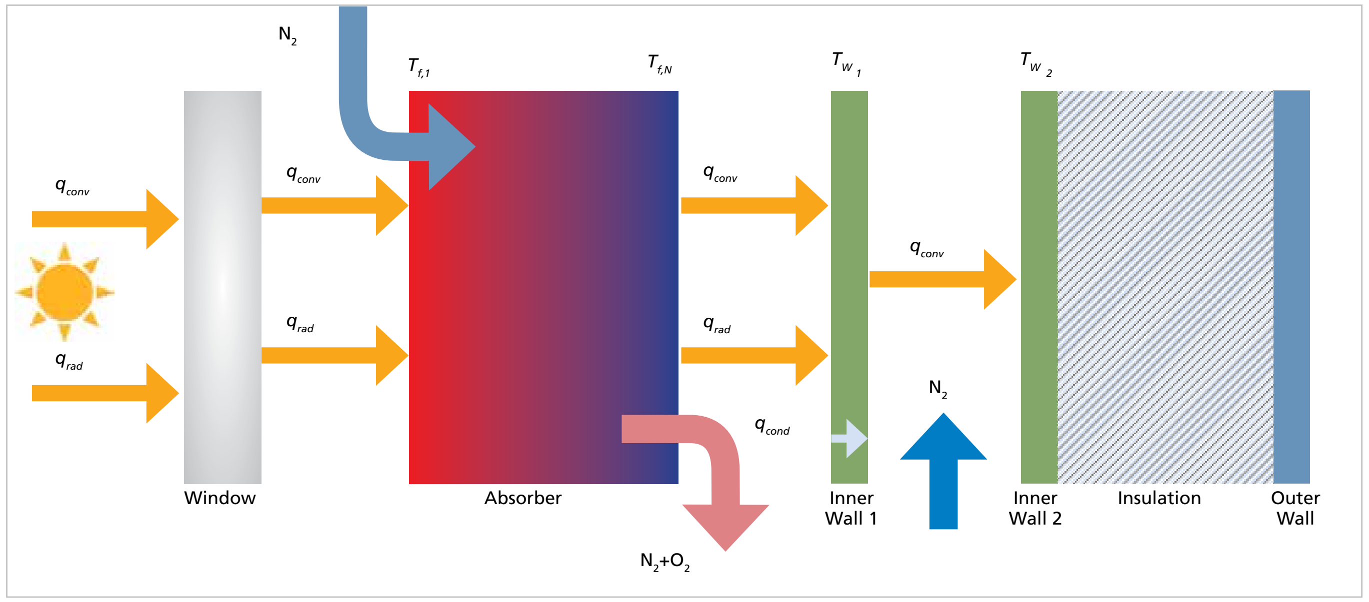
Performance of a volumetric receiver-reactor for solar water splitting

We carried out a detailed parametric investigation of a large-scale volumetric solar receiver reactor for water splitting by a 2-step redox cycle using a finite volume method model. A porous ceria absorber is its core reacting part (Figure 1). We studied its performance in different test cases, evaluating the effects of different design and operational parameters. Most important were the effects of heat recovery, sweep gas mass flow, radiation flux and porosity on the reactor performance.

The model had to solve the complete physical behavior of such a reactor, a complex transport phenomenon involving the conservation of mass, species, momentum and energy in a porous media and involving the flow of a mixture of fluids (Figure 2). It is a transient problem, consisting of a cycling behavior and including chemical reactions. The heat transfer aspect of it is complicated by itself, consisting of conduction, convection and radiation.

One finding is that in optically thick porous media the structure must be designed to optimise the radiation absorption deeper into the material, to mitigate the temperature gradient along the absorber and thereby to increase the amount of hydrogen generated. We also found that heat recovery is critical and can increase hydrogen generation by up to four orders of magnitude. The solar heat flux on the receiver can also significantly contribute to this in addition to reducing the reduction step duration. Optimisation of both design and operation of large volumetric reactors can increase the hydrogen generation rate significantly. Such numerical investigations can assess various solar reactor configurations and operational conditions before developing complex and costly experimental setups (Figure 2).

Figure 2: Model of a volumetric receiver-reactor for thermochemical hydrogen production.



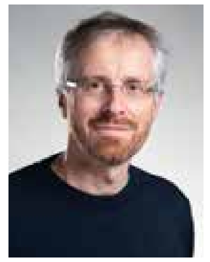
Understanding particles' thermal and mechanical behavior in solar chemical processes

The Discrete Element Method (DEM) is an established approach to model granular flows and often more accurate than continuum models. To enable the DEM simulation of solar-specific key components like particle receivers and heat exchangers, we determined contact model parameters and developed heat transfer models. The DEM helps us design dedicated components and to better understand experimental results.

In the DEM, Newton's law of motion is applied to each particle. To determine parameters for the force models, we developed a three-stage calibration procedure, based on five bulk flow experiments and surrogate functions of the respective DEM models. With this approach we determined friction and restitution coefficients of different types of particles. We also investigated how the parameters need to be scaled when the simulations are performed with larger and therefore fewer particles than in reality, thus enabling the simulation of large scale particle receivers in a reasonable period of time.

To simulate heat transfer, necessary models were developed: radiation by ray-tracing, pressure dependent conductive heat transfer between particles, heat transfer between walls and particles, transient heat conduction within receiver walls and chemical reactions for reactive particles. We applied this method successfully to design particle heaters and particle mix reactors. The simulated motion and the final location of the particles in the mix reactor perfectly represent the experimental findings (Figure 3). With DEM simulations we also reproduced and explained mass flow oscillations occurring in the CentRec® centrifugal receiver, which could not be tackled by continuum methods before.

The method is expected to play a major role in particle receiver simulations in the future, because the only drawback, the limitation to moderate particle numbers, will be mitigated with faster algorithms and larger computational resources.



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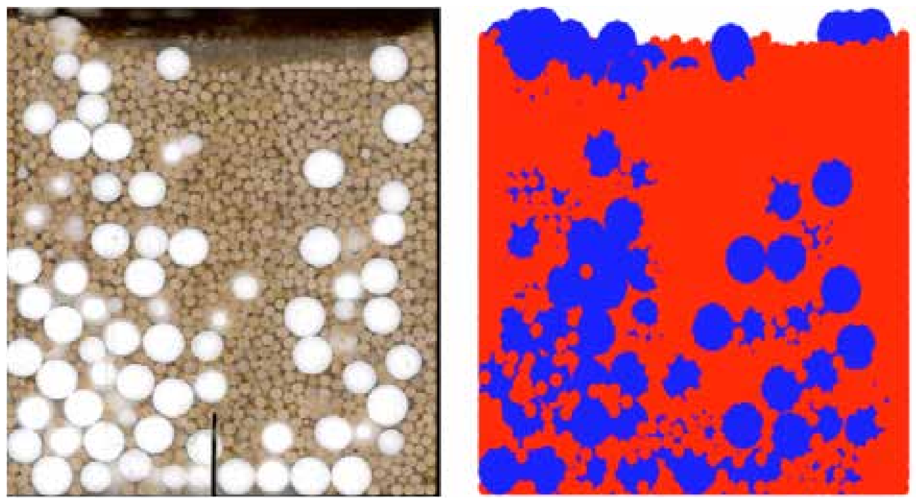

Figure 3: Particle mixture resulting from a particle mixing reactor (left: experiment; right: simulation).

Right in Time – Mitigating Uncertainties to Deliver CSP Energy on Demand

As intermittent generation electricity increases on the grid, power market price fluctuation also becomes more common. Grid operators are even more challenged to secure grid stability when balancing demand and supply depends on both intermittent renewable energy and electricity trading. Dispatchable CSP plants with storage increase clean energy power during demand peaks, while also earning peak prices; bringing benefits in wholesale energy markets to both the grid and the plants. But they need accurate delivery planning to participate successfully in wholesale markets.

Dispatching CSP plants with storage is economically optimised by accounting for weather and price forecasts, and the mechanisms of power trading on the spot market. This dispatch plan must be robust, as there are tough penalties for changes in the contracted schedule if generators do not meet their production bids. So it is critical to develop an accurate schedule, accounting for both market conditions and available solar resource.

Yet forecast uncertainties make doing so difficult. The delivery schedule is highly dependent on the type and accuracy of weather and price forecasts, so we must treat both uncertainties to ensure reliable optimisation of energy dispatch. This complex mathematical problem involving multiple factors can only be solved with appropriate flexibility planning tools.

Because flexible generation could get compensated for responding to price signals, our dispatch optimisation is very relevant not only for plant operators, but also for researchers and policy-makers.

Intelligent scheduling: dispatch optimisation with uncertainties treatment

The Institute of Solar Research developed an innovative dispatch planning strategy: the Artificial Learning Flexible Renewable Energy system Dispatch optimiser (ALFRED), designed for CSP plants expected to participate in wholesale markets.

Considering weather forecast and electricity price as input, ALFRED derives the electricity delivery schedule for a day-ahead market operation, aiming at a financial optimal with the incorporation of uncertainty information. It employs a CSP plant model in combination with a dispatch planning strategy, to develop a schedule with delivery during hours of high electricity price.

ALFRED is designed as a partitioned approach with separated algorithms for the optimisation and the uncertainty processing, accepting several types of forecasts as input. The heuristic optimisation algorithm allows the dispatch decision-making to be done with high reliability and intuitive understanding for plant operators, with capabilities to evolve over time together with knowledge enhancement of the domain.

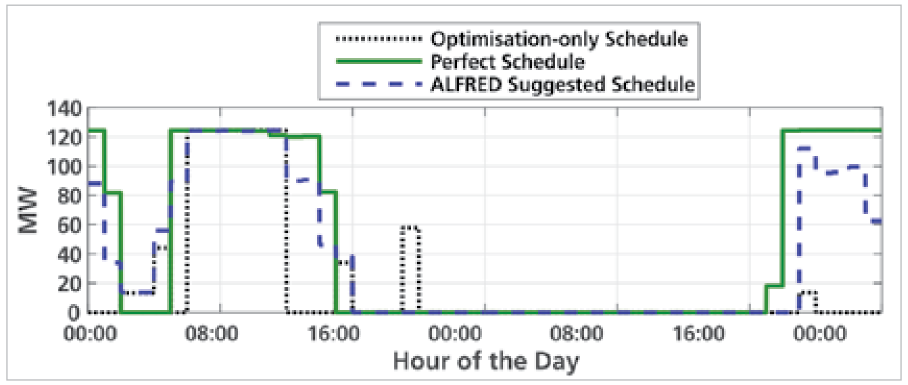

Figure 1. Optimised schedule considering a perfect forecast, a forecast product with and without uncertainty treatment.

The uncertainty treatment is then applied as a post-processing, that adjusts and defines a final delivery plan (Figure 1). Based on a machine learning algorithm, this uncertainty post-processing enables an automatic decision pattern to be generated and applied according to different conditions. By integrating historical data regarding dispatch-influencing parameters, ALFRED learns the level of uncertainty that they presented in the past.

The system identifies the cause of systematic errors, apart from understanding stochastic error patterns and, therefore, performs a suitable calibration on the optimised schedule. The advantage of calibrating the generated power production schedule instead of the underlying weather forecast is that the combination of forecasting errors and suitable strategies in various situations can also be learned and adapted.

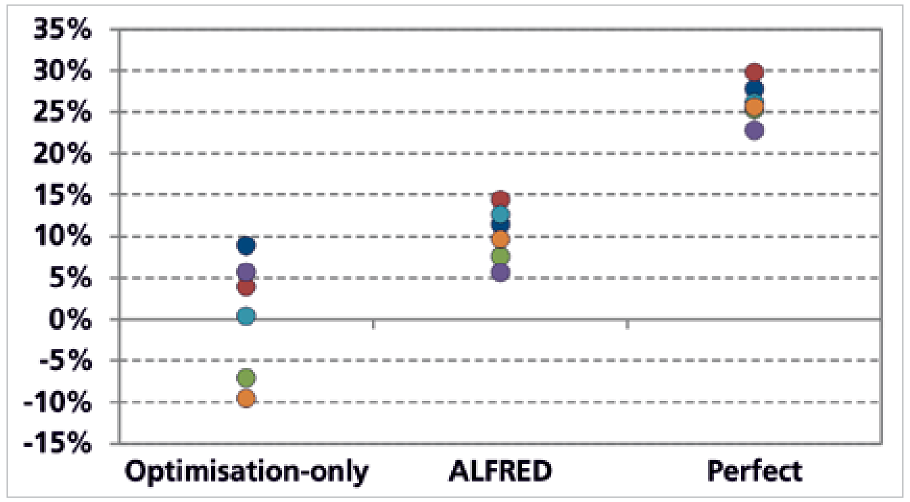

Figure 2. Annual revenue improvement rate in comparison to a solar driven approach considering six different input data sets (color dots).

Annual Simulation Results

Simulations of a 125 MW CSP tower system with ten hours of storage following ALFRED's strategy show that our proposed approach is able to improve scheduling accuracy and reduce delivery deviation while increasing income. Independent of the quality of the weather forecast, higher income is achieved when compared to solar driven or optimisation-only approaches (Figure 2).

Our post-processing algorithm effectively includes uncertainties in the dispatch planning. With this algorithm, schedule accuracy and performance reliability is not exclusively bound to weather forecasts quality, as it can be improved with the use of historical data. Considering the potential of CSP for participation in wholesale markets, our approach brings this capability one step closer to reality. In the simulations carried out, ALFRED has proven to be an effective dispatch scheduling approach, with attempts to increase delivery reliability, improve plant revenues and, therefore, contribute to a more stable and renewable grid. The optimisation and uncertainty processing algorithm described here can form a basis for future activities in the field of dispatch planning of renewable producers with storage capacity.

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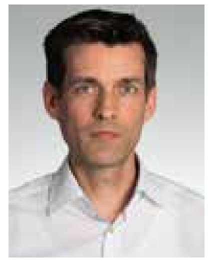


Dr.-Ing. Tobias Hirsch
Team Leader

Research Highlights

Condition Monitoring

Eye in the Sky – Airborne Condition Monitoring and Optimisation of Solar Power Plants

Condition monitoring of large solar power plants is challenging, due to their huge extent and extreme environmental conditions. Operators struggle to obtain information about malfunctions, damages, and low-performing components. So far, mainly ground-based and manual technologies have been deployed to obtain parameters characterising solar field performance. These parameters are for example: concentrator geometry, orientation of the concentrator while tracking the sun, heat losses, and soiling. Due to insufficient accuracy and spatial resolution, and limited access to the parameters and lengthy data acquisition the solar field remains a "black box". For plant operators it is therefor difficult to identify repair and maintenance measures, that are needed to secure the plant's performance over its lifetime.

A holistic approach for the qualification of solar power plants

This challenge is solved by the QFly system. A drone, or Unmanned Aerial Vehicle (UAV) carries out fully automatised data acquisition on predefined flight routes (Figure 1). Subsequent software-based data processing delivers the above mentioned performance parameters, which can be used by operators, owners and EPC contractors. The overall goal of QFly is to reduce the Levelized Cost Of Electricity (LCOE) of solar thermal energy plants by reducing the cost of condition monitoring and, at the same time, providing the operators with performance data that enables a significant improvement of the plants performance and output. The potential for LCOE reduction is in the range of 3-8 % depending on technology and power plant nominal output.

QFly combines several remote sensing techniques such as photogrammetry and deflectometry with highly sophisticated image processing. QFly refers to the software for planning the data acquisition and evaluation. For the hardware (UAV + payload), off-the-shelf customer drones are used in order to assure low costs and worldwide availability. All results obtained by QFly are represented by georeferenced data in Google Earth (Figure 2).

The most advanced field of application are geometry measurements in parabolic trough power plants. A full screening of a typical solar field (like Andasol 3) can be done in less than 4 hours, providing low resolution Slope Deviation (SD) maps and high accuracy tracking and alignment measurements (RMS < 1.5 mrad). With a different flight path, single collectors are investigated to obtain high resolution SD maps, absorber tube positions (RMS < 1 mm) and module alignment. Independent of the deployed flight pattern and payload, the status of relevant components like mirrors and absorber tubes is investigated. By using an infrared camera and adopted flight patterns, QFly can characterise up to 10 km of absorber tube per hour. Surface temperatures of the glass envelope tube are measured with an accuracy of 2 K (Figure 3). Yearly production yield analysis is obtained by using QFly measurements in ray-tracing and yield analysis software. These results have been validated by a cold solar test at the KONTAS facility within a range of ±1.5 % (2σ). In addition, ray tracer generated IAM curves have been validated with measured IAM curves.

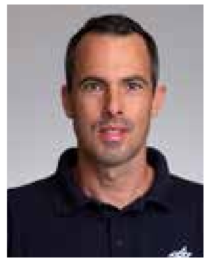
Figure 1: UAV above a parabolic trough collector during a test flight at the PSA.

System enhancements respond to the industrial needs

Several running R&D projects aim to broaden the fields of application of QFly. There is need for quicker heliostat characterisation to speed up commissioning and enhance the security and performance of solar power towers. Currently, there are two complementary approaches under development to characterise heliostat fields. A photogrammetric approach has proven to deliver the heliostat orientation with an uncertainty under 5 mrad (Figure 4). A subsequent deflectometric method is expected to further enhance the accuracy towards the sub-mrad range and also provide information about the mirror shape.

A common challenge for all solar energy technologies (CSP and PV) is how to deal with soiling of the mirrors and solar panels. We are now developing airborne soiling measurements with adequate effort, spatial resolution and accuracy, to assess these issues. A first proof of concept showed very promising results.

QFly is prepared to cope with challenges in existing and future solar power plants. The enhancement of the system to measure soiling and to include PV technology anticipates the trend towards hybrid (CSP and PV) plants. Our team is collaborating with plant operators worldwide to tailor the QFly system to these industry needs. The midterm vision of QFly is to be the leading global supplier of the most cost-efficient tool for autonomous condition monitoring.



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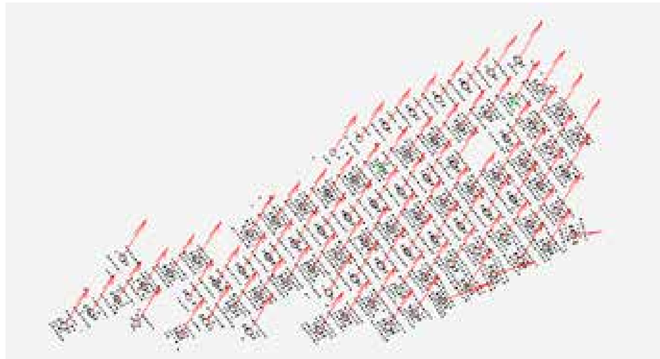


Figure 4: 3D representation of heliostat mirror corners and derived normal vectors.

Figure 2: Geo-referenced QFly results of a parabolic trough plant shown in Google Earth. (Map data ©2019 Google)

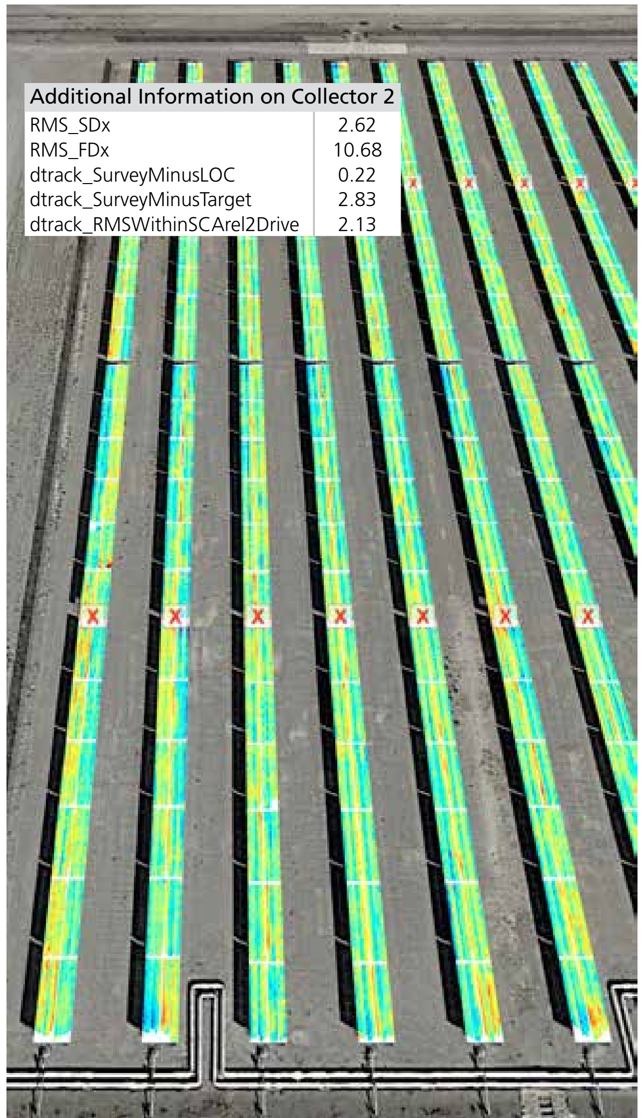
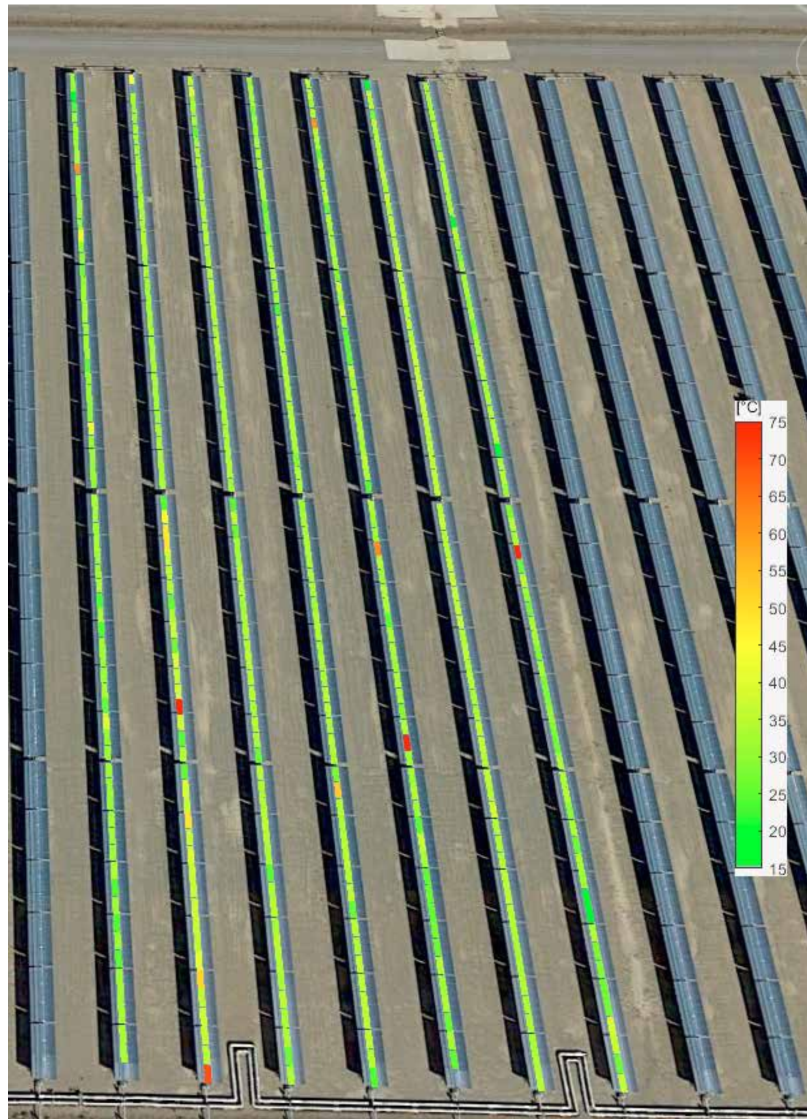


Figure 3: Georeferenced representation of glass envelope temperatures of receiver tubes. (Map data ©2019 Google)



Staring at the Sun – Solar Radiation Nowcasting for Enhanced Plant Operation

The operation of CSP power plants under variable irradiance conditions during cloud passages is a complex task. Currently CSP plants rely on one or a few pyrheliometers for DNI measurements, temperature sensors in the heat transfer fluid, and skilled plant operators to maintain acceptable efficiencies under such conditions.

Improved information on the spatial variability of the irradiance within the solar field and the expected irradiance over the next 15 minutes would enable plant operators to reach higher efficiencies. For example, knowledge of the irradiance distribution over the solar field and its forecast for the next 15 minutes would enable the operator to control the flow of the heat transfer fluid in such a way that the desired outlet temperature level can be maintained. This would increase the efficiency of the power plant. Individual plant component lifetimes would also be increased because thermal stresses due to abrupt changes in incoming radiation could be reduced. Therefore, nowcasting systems that provide DNI maps for the solar field over the next 15 minutes are of interest.

All Sky Imagers for the prediction of solar irradiance maps

To obtain such nowcasted irradiance maps we developed together with our project partners CSP Services and TSK Flagsol a system using several All Sky Imagers. An All Sky Imager uses a calibrated 180-degree fisheye lens to take pictures of the clouds above the solar field and its surroundings (Figure 1). In the photos clouds can be located using image segmentation methods. Image series can be used to derive the cloud velocity (Figure 2).

With one camera only the angular position and angular velocity of the clouds relative to the camera can be derived, but not its height and velocity in meters per second. By using two to four cameras and a stereovision approach the height and the velocity can be derived.

In combination with the usual DNI measurement station already at the power plant, the clear sky DNI can be derived and the transmittance of the cloud currently shading the pyrheliometer can be derived. To determine the transmittance of a cloud before it shades the pyrheliometer we use the relation between cloud height and transmittance. High clouds are mostly thinner than low clouds and the transmittance of clouds in the same height range changes slowly with time.

Using the cloud position and its transmittance, the nowcasting system calculates a map of the current DNI on the solar field and forecasted maps for the following 15 minutes (Figure 3). Every 30 seconds, the system provides updated radiation maps with a spatial resolution of 5x5 m for an area as big as 100 km².

Figure 1: All sky imager in the parabolic trough plant La Africana.

Nowcasting system successfully validated in real operation conditions

After the development at the Plataforma Solar de Almería we tested the system in the commercial solar power plant "La Africana" in Spain in operation for more than two years. The system has also been set up at the Jülich solar tower and in a CSP test facility in Évora, Portugal. Another application, after slight modifications, is the new research network eye2sky: More than 30 camera stations are now investigating the influence of the weather on the power grids in the region around Oldenburg. For the detailed validation of the system at these five sites we cooperated with several international partners, in particular CIEMAT, University of Evora and Meteoswiss. The system reached high accuracies compared to similar forecasts from the literature.

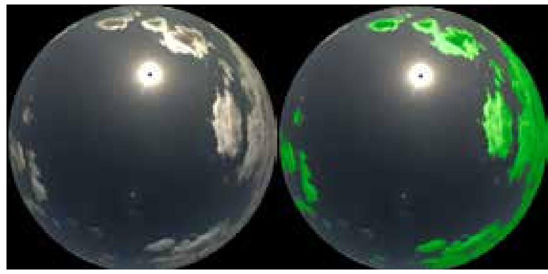
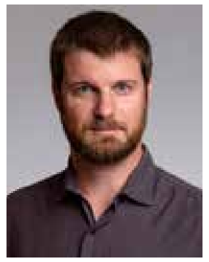


Figure 2: Left: Picture of a cloud camera.
Right: Presentation of automatically detected clouds.

Application and benefits

The potential benefit of the DNI maps was investigated in simulation studies for parabolic trough plants. We expect that the use of spatially resolved radiation information at the time of image acquisition will increase the yield of parabolic trough plants by 2% in climates similar to that of southern Spain. This significant efficiency increase can be reached even considering possible forecast errors. If the forecasts are used together with model predictive control, further increases in yield are possible. Such options with model predictive control and the application for solar tower plants are currently being investigated. Furthermore, the natural variability of solar radiation also causes fluctuations in photovoltaic (PV) production and power grids, and the data from the nowcasting system can enable a more efficient feed-in of solar power into the power grid and the forecasting of Global Horizontal Irradiance (GHI) for PV plants. This is also of interest for hybrid CSP-PV plants.



Dr. Stefan Wilbert
Team Leader

Our development partner and license holder CSP Services already offers the nowcasting system on the market. The system was also combined with a satellite and weather model-based forecasting system from the company TSK Flagsol which also offers the combined system. The satellite and model forecasts increase the forecast horizon to a period of about six hours to several days, which facilitates further enhancements of solar power plant yield.

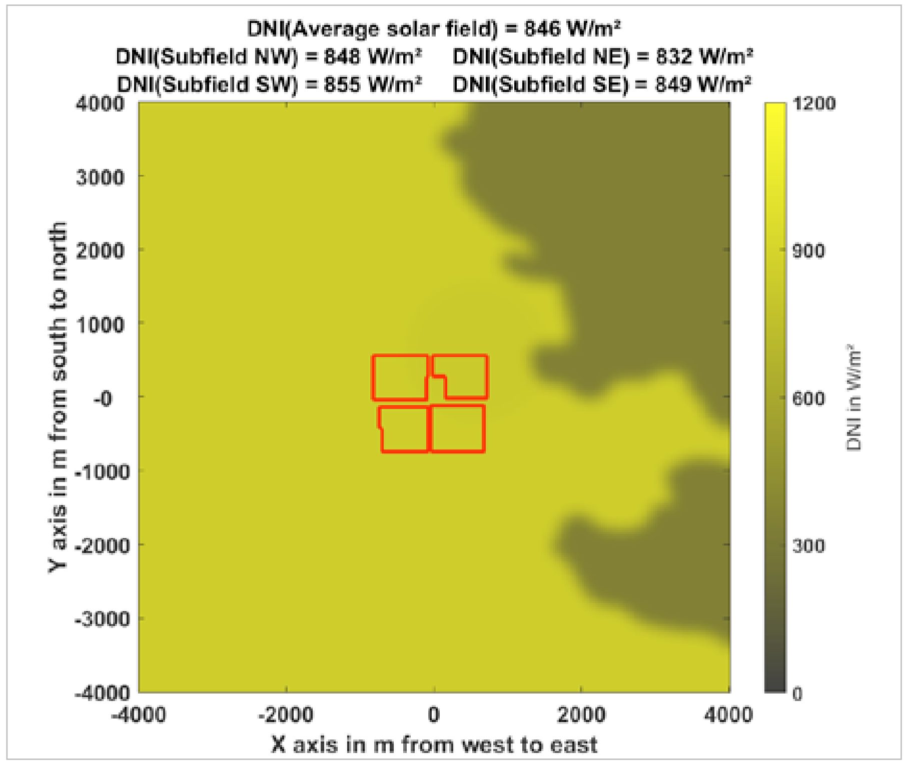


Figure 3: Local irradiance map in W/m². The outlines of the power plant are shown in red.

Tomography for Buildings – Contactless Analysis of the Building Envelope

A major challenge when plans for energy efficiency upgrades in individual buildings and districts are developed, is determining the physical parameters of buildings such as U-values, thermal masses, air infiltration rates or even the wall to window ratio (WWR) without time-consuming and expensive on-site inspections. To guarantee the effectiveness of energy retrofits, a quality control after their implementation is also desirable. So in a collaboration with DLR's remote sensing institutes, we are developing fast, accurate and inexpensive methods to characterise geometric, structural and thermal properties of building envelopes using various computer modelling and remote sensing technologies.

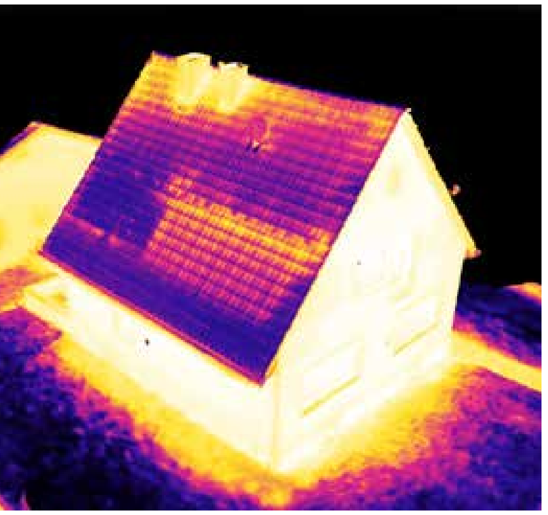


Figure 1: 3D model of a single family house with thermal infrared texture.

Geometric reconstruction of buildings

Photogrammetry offers an inexpensive, yet accurate, way to generate 3D point clouds of buildings. Using aerial images taken with a standard camera on a commercially available UAV (unmanned aerial vehicle) and a few manually measured ground control points, a point cloud of a detached house was generated. We could show that the facade lengths in this model deviated by less than 1 percent from the lengths determined by a terrestrial laser scan. Based on this point cloud a fully automised process can then compute a polygon model of the building. An image recognition algorithm detects window areas, so that a model with distinguished roof, window and facade polygons is generated. Relevant geometric information, for example, the WWR, can be easily extracted from this model. For a detached house with a simple geometry the window recognition capability reaches about 80 percent accuracy.

Analogous calculations can be performed for a complete district using aerial images taken from a light-weight aircraft. Currently, we are studying in detail the effect of view obstructions and lower resolution on accuracy.

Building-physical quantities

The 3D model is an ideal basis for further studies of the building envelope. Aerial infrared images can be mapped onto the 3D model (Figure 1). This well-known technique has been extended in a current project so that 3D models of whole districts can be automatically textured with images from aerial infrared cameras (Figure 2). Such textured models allow for an intuitive interpretation and localisation of weak spots in the building insulation. A major challenge is the quantitative interpretation of the thermal infrared measurements. We study various approaches to compensate for atmospheric influences and use ray-tracing to compensate for reflections. The aim is to determine accurate surface temperatures which allow us to classify insulation qualities of the building envelopes on a district scale. Simultaneously, time series analyses are used to determine thermal resistances and capacities of walls with infrared measurements for single buildings.

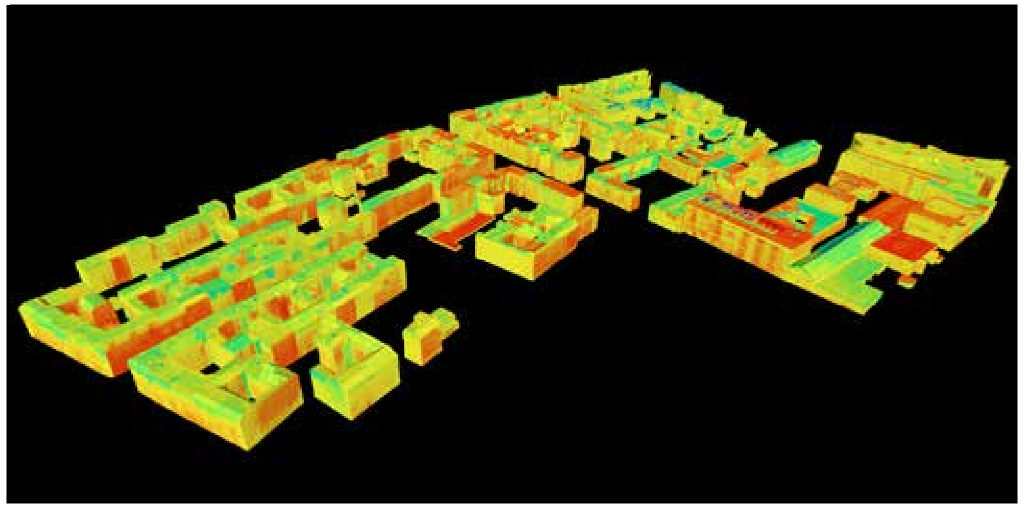


Figure 2: 3D model of a city district with thermal infrared texture.

Together with DLR's Microwaves and Radar Institute we have identified microwave radar as another very promising technique to examine the composition and thermal properties of building envelops. Emitted microwaves are reflected on layer boundaries. Recent works have shown that this allows for a detailed analysis of the 3D structure of a wall (Figure 3).

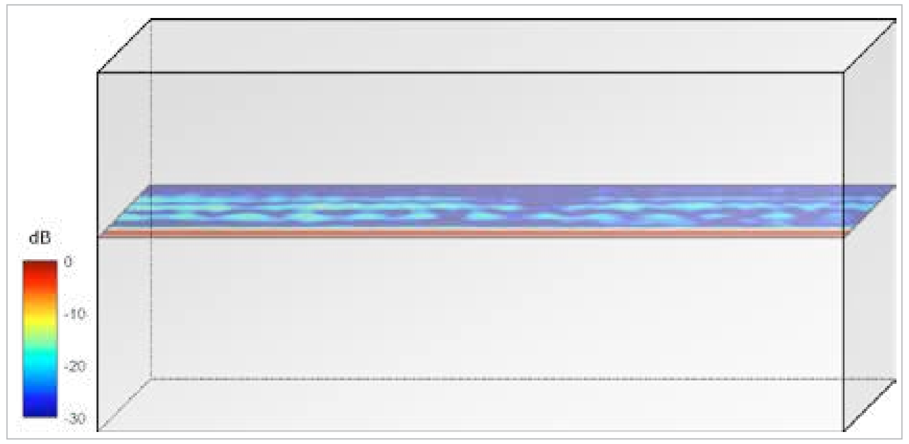


Figure 3: 3D overlay of a radar signature and a schematic depiction of a wall.

The number and thickness of layers in a wall, holes and changes in materials or reinforcements can be detected. Figure 4 shows the radar signature of a test wall with two layers of bricks and an air gap. The layer boundaries are clearly visible and the homogeneous brick type can be distinguished from the inhomogeneous type in the radar image with the naked eye. A distortion of distances appears due to variations of the speed of light in the materials. With little prior knowledge about the wall, the electromagnetic permittivity of each layer can be determined and accounted for in the data evaluation. A detailed study of correlations between the permittivity and thermal quantities of building materials also shows very promising results. For many common building materials a clear correlation between the real part of the permittivity and the thermal resistance is found. The correlation between permittivity and thermal capacity is even stronger.

Further research will show with what accuracy radar can determine thermal resistances and capacities of building envelopes. These results indicate that radar is suitable for a season-independent, contactless and fast measurement of U-values. Thermal and geometric quantities are collected in a digital building model. This allows us to use the information in energy demand calculations, dynamic simulations and, prospectively, to make a comparison between the planned and the built status of the building.

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Dr.-Ing. Björn Schiricke
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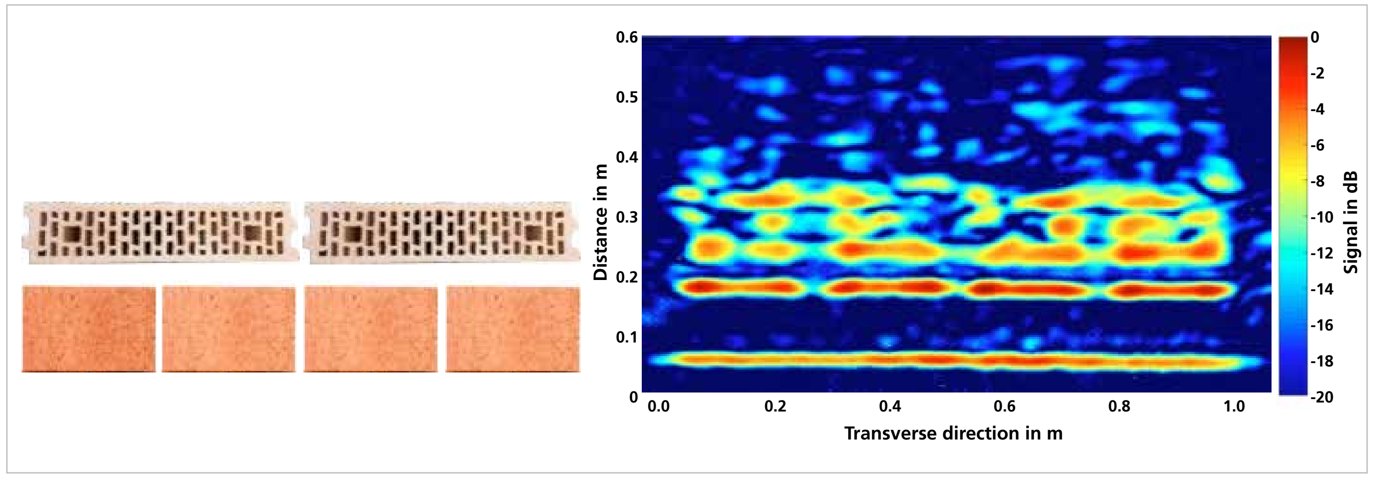


Figure 4: Left: Test wall with two layers of bricks. Right: Signature of the corresponding radar scan in one direction.

Dust in the Wind – Measuring and Modelling Circumsolar Radiation, Atmospheric Extinction and Soiling

Desert CSP holds promise, but the harsh conditions can significantly impact component performance. To operate CSP plants efficiently and to avoid additional risk margins in financing, these effects must be known. One particular challenge of deserts is the occurance of atmospheric aerosol particles which attenuate radiation and settle on plant components, reducing reflectance and transmittance. Another is a higher level of circumsolar radiation, the light that comes from the region around the sun disk. Circumsolar radiation can only be used partially by concentrating collectors, yet it is nearly all included in DNI measurements of disk irradiance. If circumsolar irradiance is misinterpreted as disk irradiance, it leads to DNI overestimations.

Correcting for circumsolar radiation

To quantify the circumsolar radiation, we developed measurement systems for two different environments and maintenance levels. One system uses two cameras to image the solar disk and the circumsolar region. The second uses pyrheliometers with different apertures. The third system uses a rotating shadowband irradiometer (Figure 1). All systems derive the relative contribution of circumsolar radiation to the DNI. The camera-based system also derives the solar radiance profile.

The systems were compared to validate their accuracy and used to derive over 10 years of circumsolar radiation data from six sites in Spain, France, UAE, Morocco and India. While the average circumsolar radiation levels vary considerably from site to site, the interannual variability analysed for two sites in Spain and UAE is small.

A ray-tracing study with a tower plant was performed with measured time series of circumsolar radiation. If circumsolar irradiance is misinterpreted as disk irradiance, overestimations of 1.5 percent and 4 percent occur for Plataforma Solar de Almeria (PSA, Spain) and Masdar (UAE), respectively. The standard solar scan results in overestimations of 0.5 percent for PSA and 2 percent for Masdar.

Figure 1: RSI measures irradiance components and circumsolar radiation.

Determining atmospheric extinction between heliostats and receiver

Between the heliostats and tower receiver, radiation gets partially lost due to atmospheric extinction caused by aerosol particles and water vapor.
We developed measurement systems based on commercially available scatterometers or transmissometers which are designed for visibility measurements and used them to determine the on-site extinction rate at four sites in Spain and Morocco (Figure 3). We added correction software for spectral and absorption effects allowing us to calculate the extinction.

Additionally, a transmittance model using only DNI measurements and other meteorological parameters usually available on prospective CSP sites was developed and validated at four sites. Applying standard extinction conditions instead of real extinction data in plant models can lead to under- or over-estimation of expected annual generation by several percent.

Characterisation and effects of soiling

Soiling also reduces plant efficiency and increases cleaning costs. We developed a measurement system for the cleanliness that is also commercially available (Figure 2). We installed prototypes in Missour, Morocco and Tabernas, Spain. The system can be applied in preliminary resource assessments, and in running power plants. It compares DNI before and after reflection at a sample mirror to obtain its reflectance. Over five years of soiling-rate data have been measured.

Figure 2: Tracked cleanliness sensor (TraCS) for real-time on site cleanlines measurement.

We also developed a cleanliness sensor for the absorber envelope tubes of parabolic trough receivers and compared soiling levels for CSP to those for PV. For CSP the soiling effect on energy output is about ten times greater than for PV as CSP loses a great part of the forward scattered radiation.

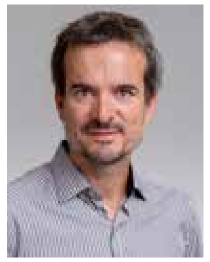
We added time-resolved soiling rate data to Greenius CSP simulation software, which improved yield analysis accuracy by more than 0.5 percent, compared to the assumption of constant field cleanliness even at the comparably clean site at PSA, where we found that improved cleaning schedules can increase the profit of a CSP project by more than 2.4 percent. We expect that sites with higher soiling rates would see greater improvements.

In addition to soiling rate, we monitored other parameters; aerosol particle concentration, wind, humidity and mirror surface properties. This data was used to develop and validate a soiling model. In a first step, ground-based measurements with particle counters and further instrumentation were used for the model. Currently the model is adapted to process particle information from numerical weather models which would allow the creation of maps and forecasts of the soiling rate.

Figure 3: FS11 Scatterometer to derive extinction rate.

Market application

The measurement techniques we developed are used in the market, and license agreements have been signed with three companies that now offer mirror soiling and circumsolar radiation measurement systems. Extinction measurements and modelled data are provided by DLR for industrial partners and further technology transfer is on its way.



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Dr.-Ing. Fabian Wolfertstetter
Project Manager

Research Highlights

Qualification

Tubular Perfection? Performance Measurement of Parabolic Trough Receivers

A central element of the parabolic trough plant is its receiver. Typical technical requirements for the receiver are an optical efficiency of at least 88 percent, heat loss under 250 W/m at 400°C, and low performance degradation over the anticipated lifetime of 25 years. This means that the selective absorber coating is required to sustain high solar absorptance of about 95 percent and low thermal emittance at 9 percent at 400°C. The anti-reflective (AR) coating of the glass envelope with a transmittance of 96 percent needs to be robust enough to withstand the elements. The glass-to-metal junctions must be robust to withstand focal line temperature gradients.

When tested at QUARZ® Center, parabolic trough receivers are usually not taken apart, but tested as full receiver units, which has several advantages: it allows for the measurement of the receiver with all interactions of the sub-parts, the reproduction of results by other laboratories, and ageing tests, while manufacturers can protect their intellectual property, as the glass is not breached. However, non-destructive performance testing is difficult to achieve due to high demands on accuracy of 1 percent for optical efficiency and 3 percent for heat loss.

Heat loss and optical efficiency test methods

The most important qualifications are tests for heat loss and optical efficiency. For these two measurements, test bench development was started in 2005 and 2009. Both test systems were the first of their kind and have been continuously improved since.

In the heat loss test bench the absorber is heated to operating temperature by electrical heater cartridges (Figure 1). Absorber temperature is measured with thermocouples at the inside surface of the absorber. As thermocouple temperature is offset to the absorber temperature by between 2 K and 10 K, receiver heat loss calculations need to be corrected as function of temperature and power. Figure 2 shows a measurement example, where a second-order polynomial – based on measured reference data – is used for this purpose. The uncertainty of the heat loss measurement is 4 percent (2σ).

Optical efficiency is measured with a linear focus solar simulator (Figure 3). Cooling the receiver with water allows for calorimetric measurement of absorbed power. While the uncertainty of the power measurement is 1.6 percent (2σ), the comparison of optical efficiency of a receiver relative to a reference receiver – important for the comparison of different receivers – reduces the uncertainty to 0.34 percent (2σ); the spatial non-uniformity of the longitudinal irradiation along the receiver length is as low as 2.3 percent.

The transfer of the solar simulator measurement to the operation in the field was investigated for various aspects: Thermal expansion of the absorber considering the difference in operation temperature between field and test bench is routinely accounted for by a correction of up to 0.7 percent, depending on bellow design. Systematic deviations of optical efficiency between solar simulator and field can be expected. Assuming idealised spectra for absorber and glass, deviations of up to 4 percent were found. However, using a set of measured spectra and considering the comparison of relative measurements – the way the measurement is typically interpreted – deviations between solar simulator and field were below 0.2 percent. This shows the effectiveness of the test in comparing the optical performance of parabolic trough receivers.

Figure 1: Electrical heater and thermocouples of the heat loss test bench.

Complementing ageing tests and standardisation

The above mentioned performance tests are complemented by a set of accelerated ageing tests: An overheating test bench keeps the receiver for a sustained period of time above maximum operating temperature. The test bench can also run thermal cycles on a receiver. A bellow fatigue test bench mechanically cycles the bellows of a heated receiver. Arrhenius-parameters of absorber coatings can be determined using a vacuum furnace and spectrophotometers. Weathering chambers and a linear abrader are used to test AR-coatings of the glass for abrasion and ageing tests.

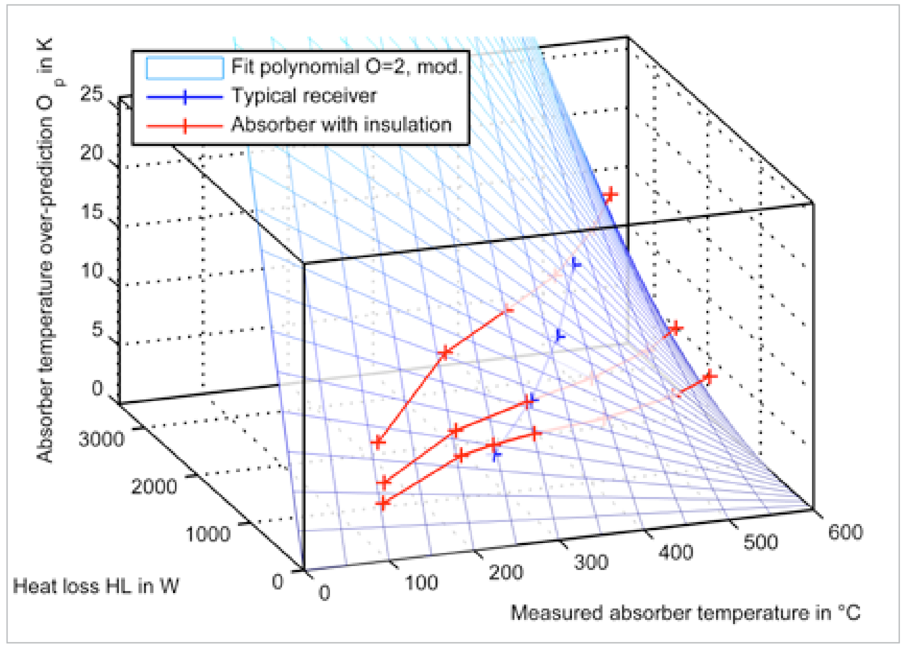


Figure 2: Example of absorber temperature correction for heat loss measurement.

We have also developed a method to determine hydrogen loading of the getters in used receivers. A drone-based IR-camera system allows for the detection of degraded receivers throughout entire fields.

We contribute to standardisation working groups, including the IEC TC117 subcommittee on parabolic trough receivers. Based on our experience we make sure that all essential aspects of the measurement are covered in the standard, that the standard is useful to differentiate the quality of the receivers, and that it provides measurement results usable in field performance calculations.

Impact

Major stakeholders, like receiver manufacturers, EPCs, and financiers have contracted measurement services through QUARZ® Center. Our activities and publications continue to make significant contributions to the field of parabolic trough receiver testing.

Dr.-Ing. Johannes Pernpeintner
Project Manager

Dr.-Ing. Björn Schiricke
Team Leader

Figure 3: View into the linear focus solar simulator test bench.

Making the Invisible Visible – Collector Manufacturing Quality Assessment

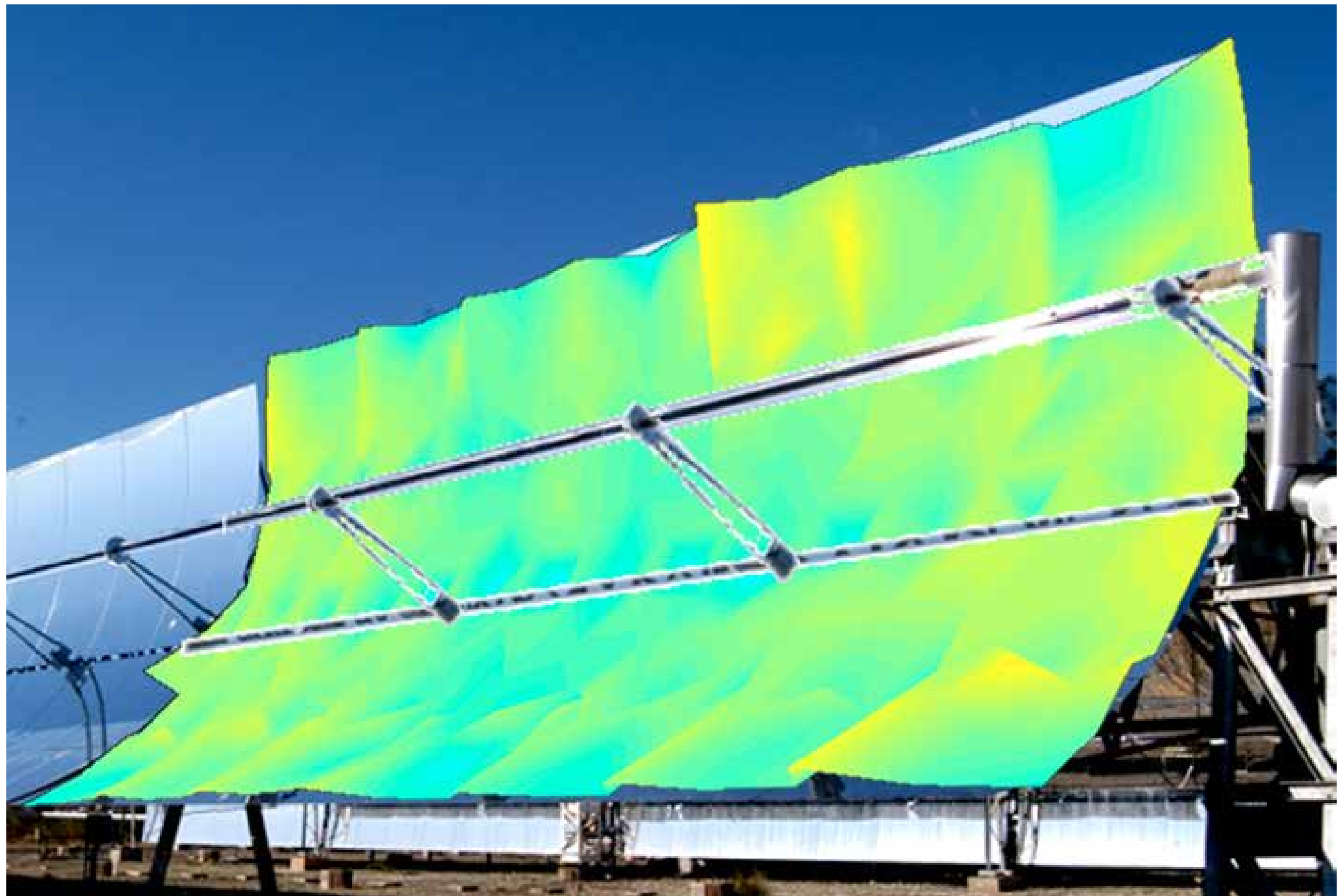
CSP collectors represent a significant share of plant costs. Their optical and thermal efficiency strongly affect annual plant output and project revenues. A one percent lower performance in a Spanish 50 MW plant with thermal storage results in a yearly economic loss of about half a million euros. So quality assessment plays a major role during collector manufacturing and plant construction. DLR Solar Research has been working on quality assessment methods and quality assurance concepts almost for 20 years. The integral concept comprises the qualification through each of the different steps; covering single components and up to large scale commissioned solar fields.

Measurement techniques and test benches for collector manufacturing quality assessment

Appropriate measurement techniques either have been developed or adapted to the rough outdoor conditions of large scale installations. The techniques used are photogrammetry for collector and absorber tube geometry and deformation (Figure 1), on-ground or airborne deflectometry for mirror slope deviations, inclinometers for collector tracking control and torsion, and infrared thermography for absorber and glass envelope temperatures. Measuring of mass flow rate, temperatures, heat transfer fluid, specific heat capacity and DNI enables us to determine the optical and thermal collector efficiencies and IAM curves. An in-house high-precision ray-tracing software interprets mirror slope deviation maps and generates intercept values and synthetic IAM curves. We successfully concluded a ring-closure between optical efficiencies determined by slope mirror measurements, and subsequent ray-tracing and thermally measured optical collector efficiency of a collector module (good agreement within ±1.5 % (2σ)).

To develop and offer these techniques to industry, we make use of DLR's unique major test benches and smaller devices. One example is the rotary test bench (KONTAS) for on-sun testing of parabolic trough collector modules and the installed components. Another large test bench operated in cooperation with PSA is to investigate the service life and failure mechanisms of rotation and expansion performing assemblies (REPAs). Two examples are ball joints and flex hoses. During the tests, temperatures, pressures, mass flow rate and cyclic mechanical movements of parabolic trough power plants are accelerated to simulate 25 year service life in a few months. Another example is an in-line flow calorimeter to measure the specific heat capacity of heat transfer fluids under operating conditions.

Figure 1: Parabolic trough collector with projection of measured deviations from ideal shape.



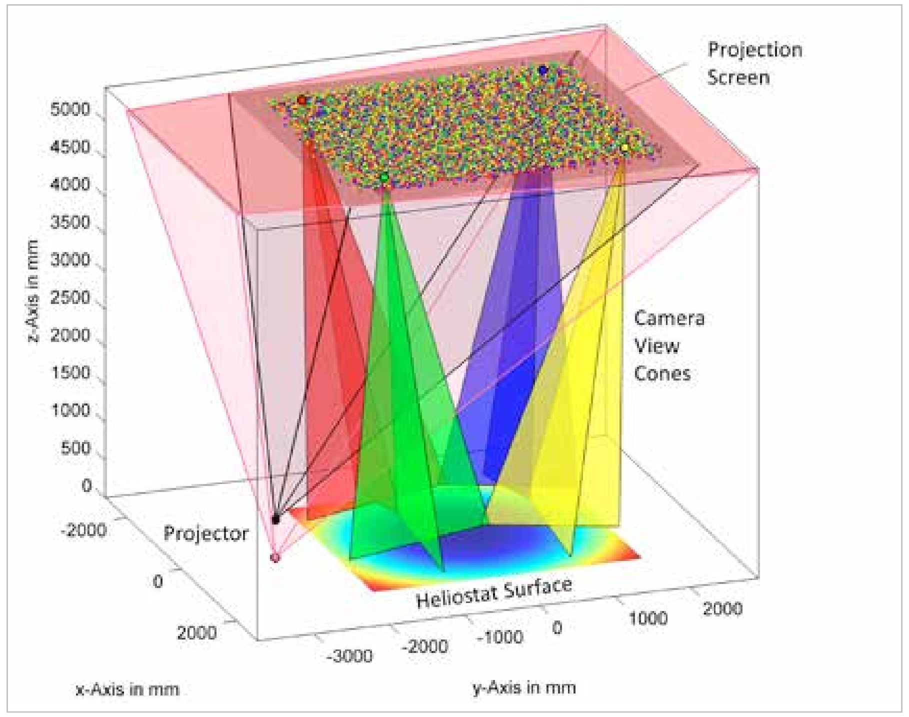
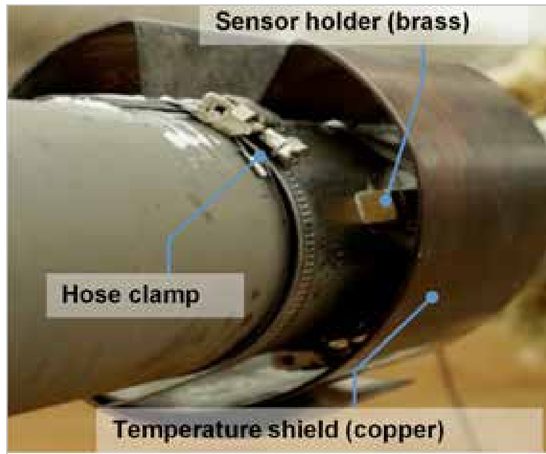


Figure 2: Inline heliostat quality control station based on deflectometry.

For the optical quality assessment of collectors in the confined spaces of manufacturing halls for mass production, we developed the photogrammetric in-line quality assurance for collectors and heliostats (QFoto), and the deflectometric in-line quality assurance for heliostats (QDec). The QDec system for heliostats (Figure 2), reaches a global measurement uncertainty accuracy of less than 0.2 mrad (1σ). The quality control step in the manufacturing line is an essential part of the integral quality control concept because on-site manufacturing of the collector structures is error-prone and a later adjustment is usually expensive. Once the collectors are mounted in the field, portable systems like the QFly measurement system for aerial inspections or the clamp-on temperature measurement devices allow the qualification of collectors or whole fields. Based on extensive tests on the KONTAS test bench and data processing we derived a temperature correction function for our clamp-on temperature measurement system (Figure 3). The developed dimensionless correction function supports numerous combinations of fluids, pipe materials, insulations, geometries, and operation conditions and is useful both for the CSP and the power and chemical industry whenever temporal, noninvasive fluid temperature readings are required. A measurement uncertainty below one Kelvin (2σ) is reached while using the general dimensionless correction.



$$\Delta\Theta_{\mathrm{f-co}} = a_1(Re + dm)^m (Pr + dn)^n \times (\Delta\Theta_{\mathrm{f-air}})^p (Bi + dq)^q \left(\lambda_{\mathrm{p}}/\lambda\right)^r \times (\lambda_{\mathrm{in}}/\lambda)^s \left(\delta_{\mathrm{p}}/d\right)^u (\delta_{\mathrm{in}}/d + dv)^v$$

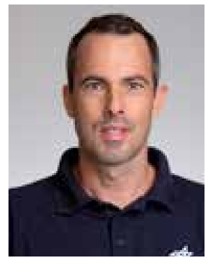
Figure 3: Clamp-on temperature measurement device with correction for in-field thermal collector qualification.

Collector quality assessment technologies developed at DLR have high market penetration

Worldwide market demand for DLR's techniques and services shows that our research and development both responds to and even anticipates industry needs. Major solar projects apply technologies developed by DLR. The QFoto system is being used in over 30 commercial CSP plants, accounting for a combined 2.2 GW – about one third of today's CSP power capacity globally. QDec systems are installed in all major CSP mirror fabrication lines.

DLR's spin-off company CSP Services led these measuring systems to market implementation and distributes them under license agreement. Our airborne optical measurement system QFly, the testing facilities KONTAS and REPA, and thermal efficiency measurements have delivered valuable services for industry customers.

Dr.-Ing. Marc Röger
Team Leader



Christoph Prahl
Project Manager

HELITEP: Testing Platform for Heliostat Qualification

Deciding factors in the efficiency of a power plant include the optical properties and the tracking accuracy of heliostats, making heliostat qualification a key element. Therefore, the institute operates a unique CSP infrastructure for heliostat testing in Germany and is continuously broadening its expertise in this research field. We innovate and develop the measurement techniques that are required to assure high efficiency solar fields.

Heliostat testing platform

Since 2016 the heliostat testing platform has offered research and industry partners an infrastructure to install their heliostats on the ground of the solar thermal test power plant in Jülich where the heliostats can be evaluated under real operating conditions (Figure 1). We use our expertise in the field of qualification of solar power plant components to contribute to an increase in efficiency and to force a reduction of heliostat costs in the long term. We offer a variety of measurement techniques that enable qualification in accordance with the SolarPACES Heliostat Performance Testing Guideline. The scope of the testing platform includes the determination of shape and structural accuracy, the determination of the tracking accuracy and reflectivity, the measurement and evaluation of the influence of external loads (wind, temperature, gravitational force) and the characterization of the reflected focal spot as well as the determination of structural properties (eigenmodes). The major measurement techniques are photogrammetry, deflectometry, modal analyses, reflectometry, and beam characterization techniques on a white target. Meteorological and atmospheric conditions are characterised additionally with 3D ultrasonic anemometer, ceilometer, aerosols monitor and a sun tracker.

Multi-camera dynamic photogrammetry system

Our use of a multi-camera photogrammetry system is unique in its application to heliostats as it allows a determination of the dynamic heliostat behavior under the influence of wind loads over time. The system consists of four locally distributed synchronised cameras which take pictures with a frequency of up to 50 Hz of the reverse side of the heliostat. Afterwards, the images of each time step are analyzed to reconstruct the geometry based on reflecting targets which cover the heliostat. The derived point clouds describe the dynamic of the concentrator triggered by the influence of its surrounding. It is a contactless measurement technique with a scalable resolution, as it fully depends on the amount of reflecting targets arranged across the concentrator. Simultaneously, various 3D ultrasonic anemometers measure the wind speed close to heliostats.

Figure 1: Stellio heliostats and the KOSMOS heliostat (DLR) on the testing platform in Jülich.

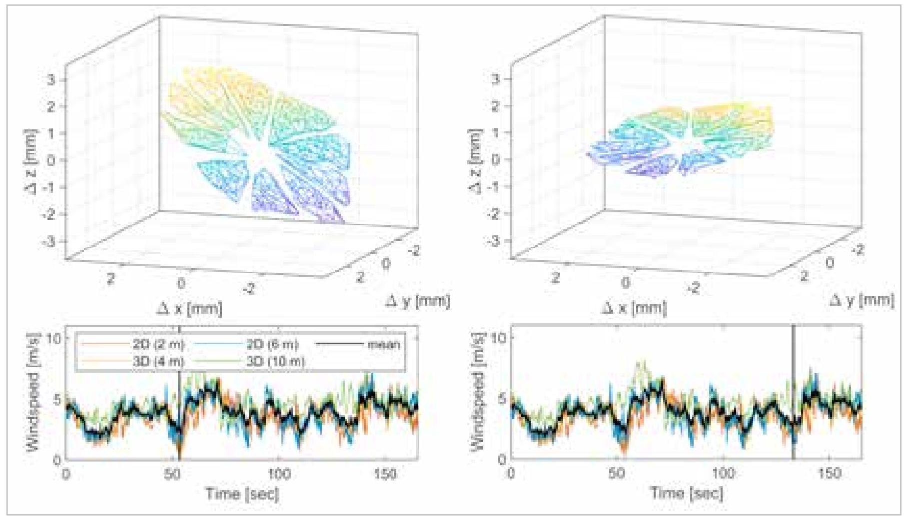


Figure 2: [top] Dynamic behavior of the Stellio heliostat for two different time steps. [bottom] Wind speed in different heights measured by 3D and 2D anemometers.

During wind loads, the concentrator starts to oscillate. This is a result of two different behaviors:
- Quasi-static behavior: Movement that correlates with slow wind speed changes.
- Resonance behavior: Superposition of eigenmodes caused by an excitation through wind loads.

Detailed insight into this behavior provides a graphical processing of the point clouds of the dynamic photogrammetry result, as exemplified by the Stellio concentrator (Figure 2). It shows a change of the optical quality, as the slope deviation of the mirror changes. In addition, wind loads cause a deviation of the concentrator normal from its desired orientation which is continuously resulting in pointing errors. Besides the movement of the concentrator, it is also possible to measure the movement of the entire heliostat including pylon, drives and suspension points. By using the multi-camera photogrammetry system, we are able to visualise wind effects, generating valuable data to expand the knowledge of heliostat behavior and locate design, manufacturing and construction errors.

The results of this measurement technique can be utilised to localise structural weaknesses or reveal considerable saving potential. In addition, the system is used to expand the knowledge of aerodynamic effects on the structure of a heliostat.

SolarPACES - Heliostat Performance Testing Guideline

A group of research and development centers and industry experts in the field of heliostats and concentrator measurement has developed the SolarPACES Heliostat Performance Testing Guideline under the auspices of DLR. The objective of the guideline is to serve as a commonly agreed protocol between research and development centers and industry in the field of heliostat performance testing.

The guideline contains an internationally reviewed, concisely defined parameter list to describe heliostats and their performance and it suggests the measurement techniques or other techniques to derive the parameters. The application of this guideline will result in homogenizing the content of heliostat test certificates which are issued by the different qualification centers. As a result, the guideline will facilitate the bankability of new heliostats.

Dr.-Ing. Marc Röger
Team Leader

Tim Schlichting
Project Manager

Hot Stuff –
Qualifying Silicone as Heat Transfer Fluid

In DLR's eight year cooperation with its industrial partner Wacker Chemie AG (WACKER), we showed that new silicone-based heat transfer fluids (Si-HTFs) have greater thermal stability and reduced gas formation rates, allowing for higher maximum operation temperatures. Between 2012 and 2015, we performed laboratory experiments on thermal stability up to 465°C and 3,000 hours (Figure 1). We showed that the formation of hydrogen is lower for HELISOL® 5A at 425°C than for the industry standard mixture of biphenyl and diphenyl oxide at only 400°C (Figure 2). This means that the hydrogen issues related to the aromatic heat transfer fluid currently used in all commercial scale power plant projects would be significantly reduced if this silicone-based fluid was used instead.

The most relevant physical-chemical properties like heat capacity, density, viscosity, thermal conductivity and pressure were verified with measurements up to the designed operating temperature range. We implemented specific laboratory experiments to enable these investigations in order to avoid the uncertainties related to the extrapolation of data measured at low temperature. Based on verified HTF properties, we then also performed several techno-economic studies and these indicated at an operating temperature of 430°C, a 5 percent reduction in LCOE.

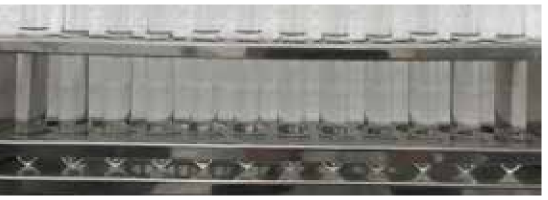


Figure 1: Samples of HELISOL® after 50 – 3000 hours (f.l.t.r.) at 440°C in a lab ageing test (no visible changes to be detected).

Silicone fluid testing facility

The next step towards market introduction of the new fluids was the application in a demonstration loop. In 2016, a DLR-led consortium with substantial industry share refurbished an existing parabolic trough test loop at PSA. The facility PROMETEO – named after Prometheus, the forward thinker, Titan god in Greek mythology – addresses all aspects of relevant loop scale demonstration with Si-HTFs. The operation temperature can be set up to 450°C while the HTF is retained for several minutes at loop outlet temperature, representing full scale applications in terms of header pipe retention times.

To demonstrate the new HTF under conditions as close to commercial operation as possible, we equipped PROMETEO with receiver tubes and rotation and expansion performing assemblies (REPAs) deriving from industry standards (Figure 3). Meanwhile, together with WACKER we improved the determination of fluid properties particularly within the designated operational temperature range above 400°C. These parameters were implemented into physical-chemical models.

Proof of concept

The consortium successfully accomplished the proof of concept for HELISOL® 5A in the summer of 2018, after operating this fluid for 480 hours at 425°C in the test loop. The robustness of the new HTF became clear when deliberate overheating at 450°C for 50 hours did not cause significant HTF degradation while being in full contact with PTC typical materials and components. Throughout operation, WACKER measured characteristic indicators of HTF degradation and we quantified the dissolved gas concentrations and physical-chemical parameters by periodically taking hot and pressurised samples from the HTF system. Both receiver tubes and REPAs were closely monitored during operation as well and performed flawlessly with the new Si-HTF.

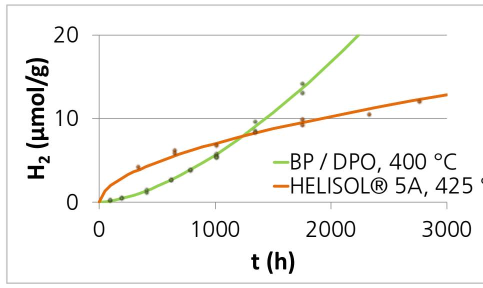
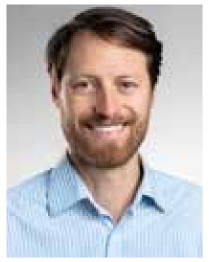


Figure 2: Formation of hydrogen from HELISOL® 5A in comparison to eutectic biphenyl (BP)/diphenyl oxide (DPO).

Safety testing

HTF operation must also be safe, in terms of both operational and ecological risks. While Si-HTF is environmentally of much less concern compared to the state-of-the-art HTF, any operational risk remained a crucial question. We investigated potentially critical reactions with water or molten salt in the laboratory. These proved to be of no concern, but the auto-ignition temperature turned out to be lower than the designated operating temperature. So DLR, WACKER, Ciemat and TÜV Nord together examined a hypothetical 2 inch HTF leakage in a full scale field test in 2018. This release test demonstrated the leakage of a PTC loop under full operation at 420°C and 15 bars. A release valve opened a 2 inch diameter cross section to the environment for 10 seconds until it was closed again. Figure 4 shows a picture series taken during the first 3 seconds of the release test until steady state conditions were met. The test demonstrated that no ignition occurs. In other words, the operation of HELISOL® 5A is of manageable risk even when it comes to major incidents. This means the HTF took another essential step towards commercialisation.

Together with WACKER's own research and development, successful results from a series of DLR tests led to the first commercial deployment of HELISOL® 5A at Royal Tech's 50 MW parabolic trough plant in Yumen, in western China. In 2017 WACKER and Royal Tech were joint winners of the SolarPACES Technical Innovation Award for the first commercial deployment of this novel high temperature silicone-based heat transfer fluid.



Christoph Hilgert
Project Manager

Figure 3: Ciemat's PROMETEO test facility at PSA for technical studies on silicone based heat transfer fluids.

Figure 4: Photo series taken during the first 3 seconds (3 pictures/second) of the 2" HELISOL® 5A release test at 420°C

Research Highlights

Materials

The Key to Hydrogen? Perovskites for Solar Thermochemical Water Splitting

Hydrogen is an important feedstock for the chemical industry, but its current production using fossil fuels causes high CO_2 emissions. By converting heat directly into chemical energy, solar thermochemical water splitting is an attractive alternative way to produce hydrogen. Oxygen is chemically removed from water using a redox material in a two-step process, and the water is split into hydrogen and oxygen as shown in Figure 1. An efficient water splitting process, however, requires using the right redox materials for the transfer of oxygen. Their oxygen affinity in the reduced state must be high enough to split water effectively, but at the same time, the oxidised material should release oxygen readily at moderate temperatures to avoid excessive heat losses and engineering issues. Finding a material that is in a perfect balance between these two contradicting requirements is challenging.

Designing the ideal redox material

We solved this challenge through materials design. The main parameter determining the oxygen affinity is the redox enthalpy change ΔH. Through a combination of computational and experimental data, we found that oxides of the perovskite type can be prepared with almost any ΔH value – this means we can essentially design them to match our needs. It allows us to locate the most suitable materials within a large dataset much more effectively than through the traditional "trial and error" approach in the laboratory.

To achieve this goal, we calculated the redox enthalpy change using density functional theory (DFT) between the material in its oxidised state (perovskite, ABO_3) and its reduced state (brownmillerite, $ABO_{2.5}$). All theoretical data has been generated using software packages associated with the Materials Project (www.materialsproject.org), an online resource of inorganic materials data to which our datasets were added. Using empirical experimental data, we then created a mathematical function describing ΔH in-between the fully oxidised and reduced state and at different temperatures. Besides the enthalpy change, the redox entropy change ΔS is crucial for the material's redox properties. ΔS under different conditions has been calculated based on statistical thermodynamics and theoretical data. By combining ΔH and ΔS to find where the Gibbs energy ΔG is zero, one can calculate the thermodynamic equilibrium at different temperatures and oxygen partial pressures.

Our dataset of over 240 perovskite materials can be used to quickly calculate the amount of oxygen released or hydrogen produced per mol of material for each material in the database. Based on this data, the amount of energy required to prepare one mol of hydrogen can then be calculated for each of those materials as shown exemplarily in Figure 2.

$$MO \rightarrow MO_{1-x} + \frac{x}{2} O_2$$

High temperature

Lower temperature

$$MO_{1-x} + x\,H_2O \rightarrow MO + x\,H_2$$

Figure 1: Concept of two-step thermochemical water splitting with reversible reduction of a metal oxide (MO).

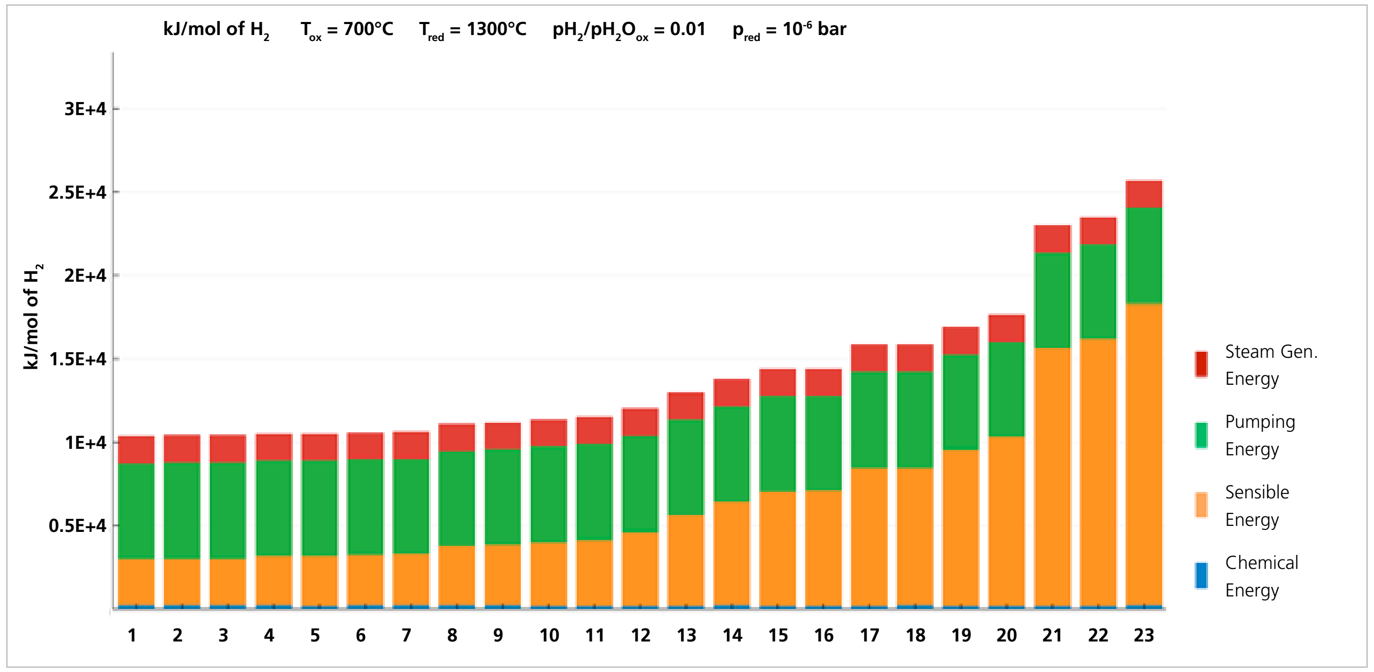


Figure 2: Exemplary result of an energetic analysis of perovskites 1-23 in our online tool.

An online materials pre-selection tool available to everyone

The entire dataset has been contributed to an online resource (MPContribs), where interactive graphs and data can be generated for different conditions (reduction temperatures and many additional parameters such as heat recovery efficiencies). This tool now serves as a means to preselect redox materials for different conditions as defined by the redox reactor and solar plant. Based on our thermodynamic calculations, the choice of materials to be analysed in the laboratory can be narrowed down significantly. While the work of a chemist and engineer is by no means made obsolete, the extent of "trial and error" in our work is reduced significantly.

The calculations show that by optimising the redox enthalpy of the material, one can lower the reduction temperature of the redox material while maintaining the same overall efficiency as in the widely considered ceria-based redox cycle. Moreover, our online tool and data allow identifying the largest energy penalties in solar fuel production. One crucial aspect is the large amount of energy required to heat the redox material from its oxidised to its reduced state (mostly sensible heat). Recovering this heat requires efficient solid-solid heat exchangers. Other important aspects include the production of excess steam in the case of materials with low H_2/H_2O conversion rates and the removal of oxygen in the reduction step, which is usually done using vacuum pumps. As an alternative to vacuum pumps, thermochemical oxygen pumps could be used. These also require redox materials such as perovskites, which can also be identified using our tool.

Overall, by combining the expertise of researchers in the field of computational materials science and those in the area of solar fuels, it is possible to optimise the solar fuel production process significantly in terms of efficiency and cost. Future work will focus on extending the existing datasets and improving their accuracy through a deeper fundamental understanding of the redox reaction and the materials involved.

Dr.-Ing. Josua Vieten
Project Manager

Under Harsh Conditions – Degradation of Solar Reflectors

The solar field typically accounts for about a third of the cost of a CSP plant. To reassure investors that there are few investment risks, manufacturers and developers must be able to accurately gauge the rate at which solar reflectors are likely to degrade over the typical 25 year lifetime in an average Power Purchase Agreement (PPA). At CIEMAT's Plataforma Solar de Almería (PSA), we at DLR's Institute of Solar Research and CIEMAT have been intensively researching mirror lifetime prediction methods at the Optical Ageing Characterisation laboratory (OPAC) since 2010.

In order to investigate the causes and extent of the degradation of solar reflectors, our scientists are using the following different approaches:

Outdoor exposure

The institute participates in an international network of outdoor exposure sites at various locations. We have been exposing mirror samples to extreme UV-irradiance, severe sand erosion and high corrosivity at 17 sites with exposure times from two up to seven years (Figure 1). Prerequisite for the successful functioning of the network is a close collaboration with the member research institutes from Spain, Morocco, UAE, Chile and France. Examples of such locations are Chajnantor in Chile at an altitude of more than 5,000 metres and Zagora and Misour in Morocco. Most of the exposure sites are located close to meteorological stations, which collect data concerning irradiance, temperature, wind speed and ambient relative humidity. One factor to assess the different exposure sites is corrosivity, determined by measuring the annual weight loss of reference copper, steel, aluminum and zinc samples according to ISO 9223. In addition, the exposure sites are categorised into three "erosivity" classes, based on the measured erosion defect density on the glass surface of the exposed samples.

We identified corrosion of the silver layer and erosion of the glass surface (Figure 4) to be the predominant degradation mechanisms of silvered-glass reflectors.

Accelerated ageing testing

A large set of accelerated ageing tests has been conducted with silvered-glass mirrors from different manufacturers. Several standardised tests from the glazing, automotive and plastic industry were screened. The most representative test to reproduce localised silver corrosion pits and edge-corrosion was found to be the Copper Accelerated Salt Spray (CASS) test according to ISO 9227 (Figure 2). But none of the tests did realistically simulate glass erosion due to blowing dust and sand particles. So the DLR and CIEMAT solar research teams at PSA developed a novel sand erosion chamber, able to mimic the degradation pattern from outdoor exposed samples (Figure 3).

Figure 1: Outdoor exposure testing of solar reflector samples at CIEMAT's PSA.

Figure 2: Salt spray testing of reflector samples according to ISO 9227 to accelerate silver corrosion processes.

Sample characterisation techniques

Our researchers use optical microscopy, spectral-hemispherical and monochromatic-specular reflectance measurements to optically characterise samples from outdoor and accelerated tests. In addition, we developed and patented novel characterisation techniques for improved degradation detection. Especially the in-house-developed microscopic and photographic image analysis tools have proven to be valuable to derive correlations between outdoor exposure and accelerated testing. Over our test period, a database containing more than 3,000 measurements of silvered-glass mirrors has been built, containing information on degradation rates of different mirror manufacturers.

Figure 3: Custom-made sand erosion chamber to mimic sand and dust storms.

Lifetime prediction

Lifetime prediction uses the information from correlating outdoor exposure with accelerated ageing. Each degradation mechanism requires its individual correlation and test conditions (Figure 4). The correlation for silver corrosion was determined by measuring the corroded area during outdoor exposure and in the accelerated CASS test. For erosion, the correlation was derived by measuring impact density and defect sizes outdoors and after ageing in the accelerated erosion chamber. The combination of both accelerated tests allows to quickly estimate the expected lifetime of novel materials at exposure sites of different corrosivity and erosivity.

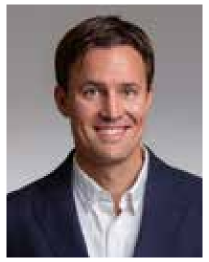
Degradation mechanism	Silver corrosion	Glass erosion
Outdoor exposure testing	 after 1 year of outdoor exposure in Tan Tan, Morocco	 after 2 years of outdoor exposure in Zagora, Morocco
Accelerated ageing testing	after 240h of CASS testing according to ISO 9227 	after sand erosion test in custom made chamber 

Figure 4: Comparison of degradation mechanisms in outdoor and accelerated ageing tests.

Application

Our methodology is currently being applied to estimate the lifetime of novel protective coatings for silvered-glass mirrors in different environments. We are investigating a lead-free and five types of low-cost protective coatings. In the past, nine different types of transparent top-coatings for aluminum reflectors have been qualified.

The work also contributed to standardise reflector characterisation techniques, which led to the Spanish standard UNE 206016:2018 and to the SolarPACES Reflectance and Aluminum Reflector Accelerated Ageing guidelines.



Dr.-Ing. Florian Sutter
Team Leader

Black is Black? Absorbing Solar Flux for a Lifetime

The absorber coating of a solar tower receiver must withstand high thermal stresses in harsh desert conditions. We aim to find absorber coatings with increased lifetime and performance compared to the state-of-the-art. In order to simplify O&M procedures, paint curing processes via concentrated solar energy are being investigated, which enable the curing directly on top of the solar tower.

At present, degradation of absorber coatings results in expensive recoating procedures: the old paint needs to be removed from the receiver tubes by sandblasting and then the entire panel needs to be recoated and cured. Usually the panels are dismounted from the tower, the recoating process is done in a workshop on the ground and the paint cured in large furnaces – a maintenance procedure with high down-time cost. For example, a maintenance day, with no electricity produced, means losses up to 200,000 USD for a plant such as Ivanpah (California, USA). Therefore high absorber coating durability is key to solar tower plant profitability.

State-of-the-art Pyromark 2,500 coating reaches a high solar absorptance of α_s=97 %. However, the coating also shows a high thermal emittance ($\varepsilon_{750°C}$= 87s%) and fast degradation rates (2 % absorptance loss per year was measured for the SolarTwo pilot plant).

Accelerated ageing testing

A variety of different types of novel absorber coatings for temperatures up to 750°C have been tested on different substrate materials. The degradation mechanisms of the coated absorber tubes were analysed microscopically at several points in time during durability testing (Figure 1). In addition, solar absorptance and thermal emittance were determined to compute the optical coating efficiency.

Figure 1: Microscopic analysis of failure modes of absorber coating after durability testing.

Accelerated ageing testing was carried out in four sets of tests:

- Isothermal furnace testing: used for basic screening of the different substrate/coating combinations. Isothermal testing is conducted at temperatures between 650 and 800°C for typically 2,000 hours.
- Climate chamber testing: the humidity (ISO 6270-2), humidity freeze (IEC 62108, 10.8), sand erosion (custom-designed test), salt spray (ISO 9227) and damp heat (IEC 62108, 10.7b) tests are used to mimic environmental corrosion and erosion processes at ambient temperature during night-time or plant shutdown.
- High solar flux testing: a custom test bench was designed and installed at the dish concentrator at CIEMAT's Plataforma Solar de Almería (PSA) (Figure 2). Thermal cycling of 15 tubular samples can be conducted in parallel. A typical cycle consists of heating from 200 to 750°C, holding for 30 minutes and cooling back to 200°C, with realistic thermal gradients of 30 K/min, and average flux on each sample of 350 kW/m². This solar cycling mimics typical operation conditions during start-up, shut-down or cloud-passages. The test runs automatically and parameters such as temperature, flux and thermal gradients are easily adjustable, if required.
- Combined testing: a demanding testing sequence was developed for promising coating/substrate combinations: 1,000 hours of isothermal testing, 50 solar cycles, 100 hours of humidity testing (ISO 6270-2) and again 50 solar cycles. This programme is used to mimic operation conditions and condensation on the receiver tubes overnight.

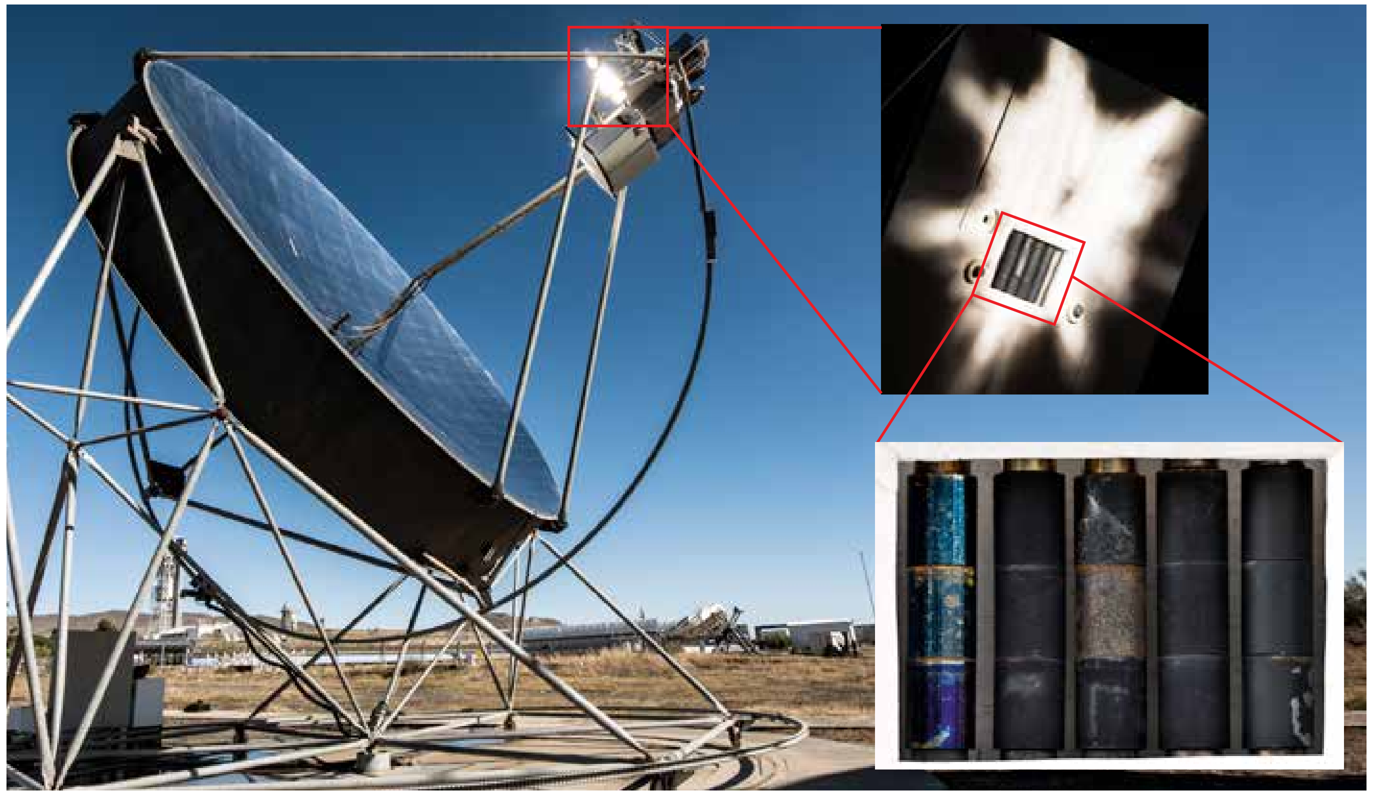


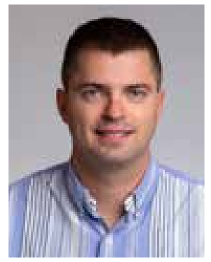
Figure 2: Accelerated ageing testing of absorber coatings in the dish concentrator test bench at CIEMAT's PSA.

Among the tested coatings, the highest optical efficiency was measured for a novel solar selective coating, achieving α_s=95 %, $\varepsilon_{750°C}$ = 28%. However, the coating showed fast degradation throughout the conducted durability tests, requiring formulation optimisation to enhance lifetime. On the other hand, two novel non-selective coatings were identified as very promising: they showed similar optical performance as the state-of-the-art Pyromark 2,500 and excellent durability in the combined testing sequence. As a result of our testing activity, one of those identified coatings will be deployed in the commercial receiver of the 100 MW_{el} DEWA solar tower project in Dubai.

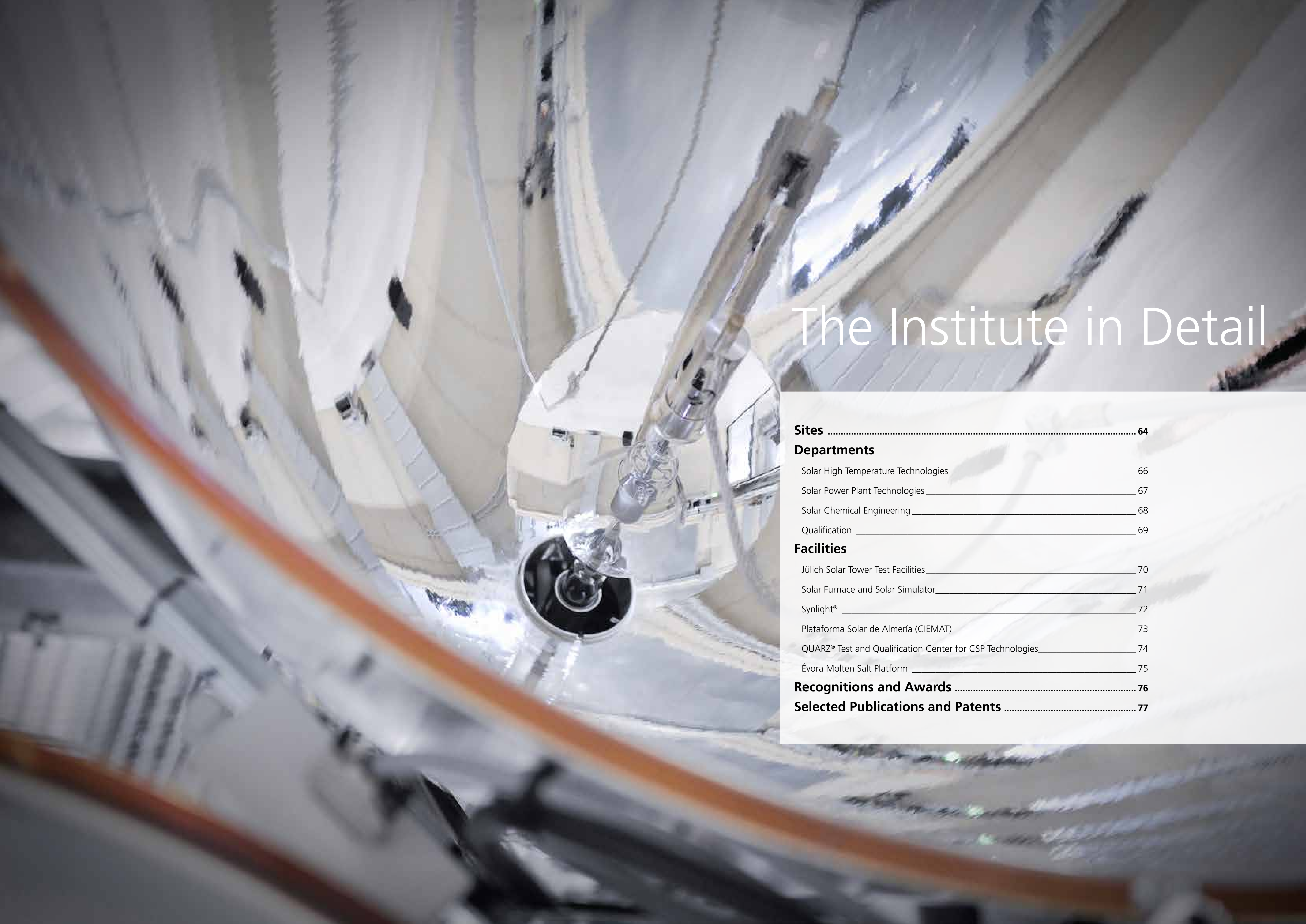
Solar curing experiments

Solar curing experiments were conducted at the dish concentrator at PSA (Figure 2) to demonstrate that this recoating process of the receiver can also be done on top of the tower, eliminating the need to dismantle the receiver panels. Several freshly painted samples were cured using solar flux. It was possible to follow the specified curing profile with several interruptions due to clouds and night-time. Also the precision of the temperature set points was lower (±50°C) with respect to the defined temperature setpoint profile. In spite of those effects, the solar cured samples on Inconel 617 and Haynes 230 substrates showed similar optical and durability performance as oven-cured samples, achieving a stable high solar absorptance of α_s=97%. These experiments confirm the attractiveness of solar curing of receiver coatings to reduce O&M cost.

Dr.-Ing. Florian Sutter
Team Leader



Simon Caron
Doctoral Candidate



The Institute in Detail

Sites

The institute's staff works at four locations in Germany and Spain. At each site the institute's researchers have different unique testing facilities, measuring devices or laboratories at their disposal. In Spain, the institute has permanent access to Europe's largest research facility for concentrating solar technologies, the Plataforma Solar de Almería, owned and operated by the Spanish research centre CIEMAT. Highlights at our German sites are our large-scale research facilities: the Solar Furnace and a solar simulator in Cologne, the Jülich Solar Tower and the largest solar simulator Synlight® in Jülich.

Cologne

The head office of the Institute of Solar Research is located at the DLR headquarters in Cologne, where the conversion of solar energy into usable energy has been researched for more than 40 years. At the Cologne headquarters the institute employs a staff of 52 people.

Solar Furnace in Cologne.

Here the institute operates various test facilities, laboratories and Germany's only solar furnace. In the laboratory of the test and qualification centre QUARZ®, we examine the quality of power plant components for the CSP industry.

Mounting of the particle receiver CentRec® at the Jülich Solar Tower's research level in May 2017.

The SOPRAN demonstration plant tests and verifies the performance of parabolic trough solar collectors in supplying direct heat for industry steam heat needs. Another test stand, SoCratus (Solar Concentrator with a Rectangular Flat Focus) is designed for experimental studies with photocatalytic and photoelectrochemical systems under concentrated solar irradiation. An interdisciplinary group of DLR scientists, comprising solar researchers from the institute's Solar Process Engineering Department and researchers from the Institute for Materials Research and Engineering Thermodynamics, work together to develop ceramic materials and thermal storage technology in the CeraStorE building.

Jülich

The Jülich site, in the Rhenish lignite mining district between Cologne and Aachen, employs a staff of 32. Two large-scale research facilities form a worldwide unique research infrastructure for experiments with concentrated sunlight: the Jülich Solar Tower, Germany's only solar tower power plant, and Synlight®, the world's largest solar simulator. Since 2011 the solar tower has been part of the institute and is used exclusively for research purposes. It is equipped with a research level, which can host temporary test installations. A second solar tower with three additional research levels is currently under construction. Both towers' primary research topics are solar tower technology and the related processes, as well as thermochemical processes for the production of solar fuels.

In March 2017, the institute opened the Synlight® plant for experiments, using simulated sunlight. It offers ideal conditions for solar radiation tests for the production of solar fuels, but is also suited for testing components of solar plants, aviation or aerospace.

Stuttgart

Until the institute was founded in 2011, DLR Solar Research was a department within the Stuttgart Institute of Engineering Thermodynamics. The Institute of Solar Research has therefore been present at the Stuttgart site with a strong team since its inception. Today, 25 employees work here.

Particle Receiver CentRec® in the High Temperature Laboratory Stuttgart.

The researchers work on the development of new technologies, materials and processes for solar tower and parabolic trough power plants. For tests with different heat transfer materials at over 1,000°C a high-temperature heat laboratory (HITS) has been installed on the site. An outstanding project being developed by a Stuttgart team is CentRec®, an innovative centrifugal particle receiver concept using ceramic particles as heat transfer material.

Almería and Plataforma Solar de Almería

The Plataforma Solar de Almería (PSA) is situated on the edge of Tabernas Desert, in the province of Almería in southeast Spain.

The owner and operator is the Spanish research centre for energy, environmental studies and technology, CIEMAT. Since 1980, researchers at PSA have been exploiting solar energy outdoors for testing and developing high-temperature CSP technologies. DLR played a major role in the planning and construction of the site. Today, 25 DLR employees work between PSA and a town office in Almería. Since the very beginning DLR researchers have worked at the site in solar technology testing and development work. At PSA, DLR scientists work in many projects in close co-operation with their Spanish colleagues from CIEMAT. DLR and CIEMAT operate unique test installations which are developed to answer industrial application needs. The Meteorological Station for Solar Technologies (METAS) is operated in close collaboration with CIEMAT. It is equipped with state-of-the-art measuring devices to determine meteorological parameters that are relevant for solar energy.

Flexible tube connections used in solar trough plants can be examined in a special REPA test rig at PSA to locate and solve any functional problems, and to test long term durability.

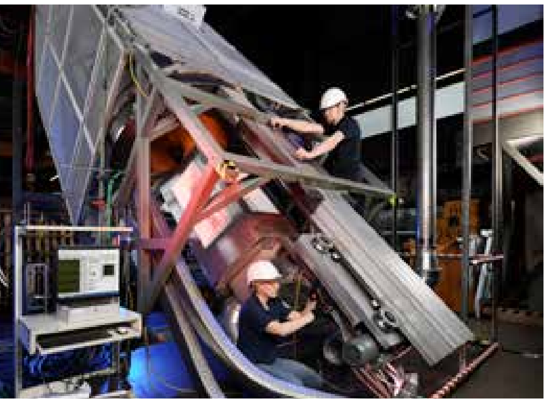
One of the larger test installations at PSA is the PROMETEO test facility, also developed in a co-operation between CIEMAT and DLR. This enables the demonstration of safe operation of novel heat transfer fluids, for example, of silicone oil.

Elke Reuschenbach
Public Relations

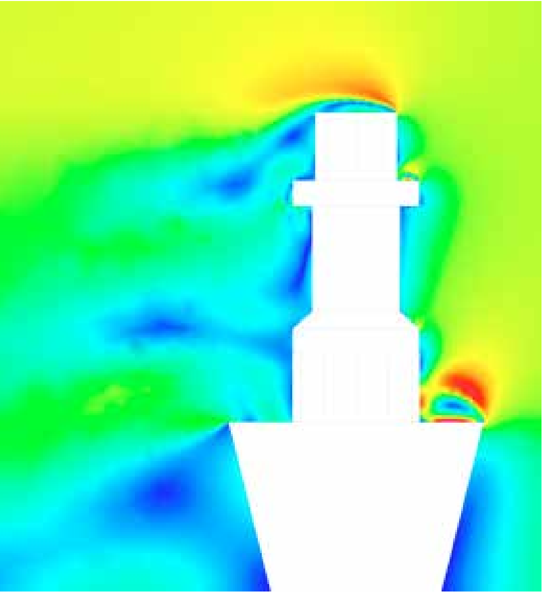
Another development by the Almeria team is QFly, a now commercial system for the airborne qualification of complete solar power plants using drones.

Aerial view of CIEMAT's Plataforma Solar de Almería.

Solar High Temperature Technologies



Assembly of the CentRec® receiver prototype for cold pretests.



CFD simulation for convective losses around a receiver.

Dr.-Ing. Reiner Buck
Head of Department

R&D objectives

The department targets cost reductions for solar power and process heat systems in parabolic trough and solar tower technology. The team has long-term experience in high-temperature concentrating solar systems.

Specific R&D objectives:
- Improve performance and reduce cost of components by design improvements and validation from modelling to full scale
- Develop simulation tools and models for layout and detailed analysis of component characteristics, including experimental model validation
- Develop advanced dispatch strategies based on forecast data for different power cycles (steam, sCO_2), including thermal storage and hybridisation to reduce levelised cost of electricity or to increase revenues
- Design, simulate and optimise electrical storage systems (Power-to-Heat-to-Power), using CSP-based technologies

Structure of the department

The department now combines the activities of line-focusing and point-focusing systems previously assigned to two separate departments. Its 28 staff members are split among three research groups, located in Stuttgart and Cologne:
- **System modelling** (Dr.-Ing. Tobias Hirsch, 9 members)
  We optimise system configurations of solar thermal power and process heat systems, including dispatch strategies that include weather and demand forecasts.
- **Fluid systems** (Klaus Hennecke, 7 members)
  We develop solar thermal technologies for both trough and tower systems, primarily using molten salt, but also for liquid metals and steam. We also investigate and test innovative receiver concepts, system components and O&M improvements.
- **Particle systems** (Martina Neises-von Puttkamer, 10 members)
  We develop particle receivers and systems, mainly the centrifugal particle receiver, but also particle heat exchangers, for example for process heat applications.

Main competencies

- Simulation of receivers and other system components, using FEM, CFD and DEM tools for thermo-mechanical analysis of components, and for fluid flow and heat transfer simulations. Simulations are used for design optimisation, performance prediction and improvement of operation strategies.
- Detailed performance simulations of complete solar power systems for use in system layout optimisation and techno-economic analysis.
- Operation of parabolic trough and solar tower systems, including dispatch optimisation of solar plants with storage.
- Expertise in various heat transfer media (molten salt, particles, liquid metal).

Solar Power Plant Technologies

R&D objectives

The mission of the department is applied R&D to support the development of "intelligent" solar tower power plants, focusing on their operation and control, their numerical simulation, and on their power blocks.

This is done in synergy with the operation of DLR's experimental solar tower in Jülich, consisting of an 11 MW solar field with more than 2,000 heliostats, an open volumetric receiver with one hour of thermal energy storage and a full 1.5 MW steam power plant, plus its own integrated research platform.

Jülich is currently being extended by a second tower with three further research platforms, equipped with molten salt and particle cycles and various gas supplies for solar chemical applications. At the same time a major overhaul of the heliostat field and its control hardware and software is under way.

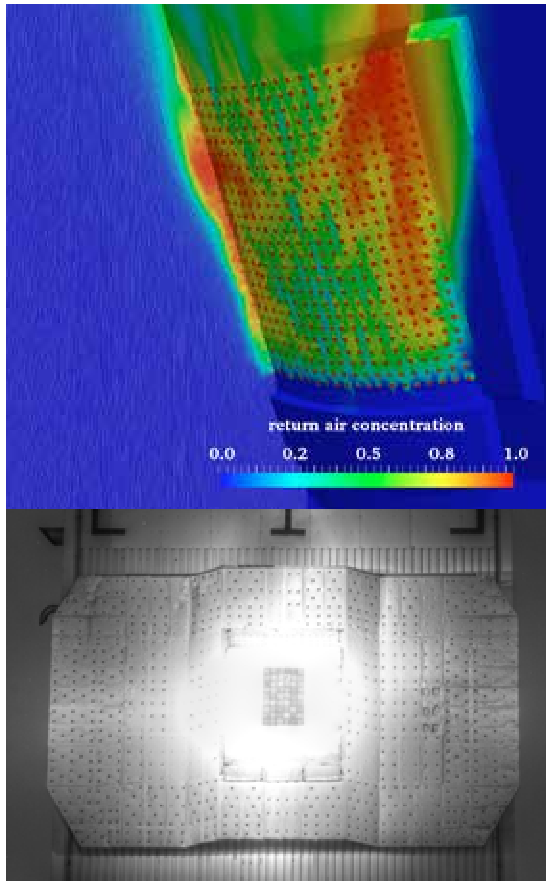
Specific R&D objectives:
- Increase automated and autonomous operation for improved solar yield and reduced OPEX
- Test and demonstrate various solar tower technologies and evaluate operating experience
- Close the current gap between solar tower and traditional steam power plant technologies

Structure of the department

The department consists of 25 persons and is divided into three teams:
- **Simulation and open volumetric air systems** (Peter Schwarzbözl, 10 members)
  Covers software-related research in simulations and control, situated in both Cologne and Jülich. Also researching open volumetric air receiver systems.
- **Jülich solar power tower plant** (Felix Göhring, 9 members)
  Operates the Jülich Solar Tower, including all testing activities and corresponding measurements, and runs power plant and heliostat design-related R&D activities.
- **Jülich site management and technical support** (Thomas Hartz, 4 members)
  Handles all site-related responsibilities and cross-sectional tasks which were assigned to the department in addition to its R&D activities.

Main competencies

- Operation of the solar tower and research platforms
- Heliostat design and control, layout of heliostat field and solar tower plant
- Simulation of ray-tracing, lifetime receiver durability, and dynamic processes and measurements such as heat flux
- Engineering artificial intelligence, big data and state-of-the-art software
- Development of open volumetric air receiver technology
- Power block and thermal energy storage improvements



CFD simulation and testing of a novel open volumetric receiver (2019).

Dr.-Ing. Kai Wieghardt
Head of Department

Solar Chemical Engineering

Reactor development and testing in the Solar Furnace (top) and SOKRATUS (bottom).

R&D objectives

The strategy is to study the conversion of solar radiation and abundant resources like water and air into fuels, especially hydrogen, ammonia and synthetic liquid hydrocarbons, and to use these competences for other chemical or material processes.

Specific R&D objectives:
– Develop components for solar thermochemical, photochemical, and photoelectrochemical processes
– Develop simulation tools for the layout and analysis of components and processes
– Techno-economic analysis
– Scale-up of solar chemical technologies into the megawatt range
– Analysis and improvement of heat transfer fluids

Structure of the department

The department consists of 35 persons – 17 scientists, 5 Post-Docs and visiting scientists (4 of them funded by the DLR-DAAD scholarship programme), 5 doctoral students and 8 engineers – plus, in 2019, 11 master students. It is organised in three teams:

– **High temperature processes > 500°C** (Dr. Martin Roeb, 22 members)
Development of thermochemical processes including redox cycles for hydrogen, syngas and ammonia production and processes for materials production. The team also operates the solar furnace and high-flux solar simulator facilities in Cologne.
– **Low temperature processes < 500°C** (Dr. Christian Jung, 6 members)
Development of chemical engineering processes below 500°C including photelectrochemical reactor development, photochemical processes and the qualification and improvement of heat transfer fluids. The team operates the rectangular flat focus facility SoCRatus (Solar Concentrator with a Rectangular Flat Focus) in Cologne.
– **Scale-up of processes** (Dennis Thomey, 6 members)
Scale-up of technologies for operation in Synlight and on the solar towers and development of the necessary control software based on dynamic models. The team operates the Synlight® facility in Jülich.

Main competencies

Prof. Dr. Christian Sattler
Head of Department

– Solar processes for fuel production, especially hydrogen as an energy carrier, as a precursor for gaseous and liquid carbon-based energy vectors and ammonia, or as a reagent in other chemical processes, and for materials production for example of aluminum, cement, phosphate, sulfur, solar water treatment, sea water desalination and synthesis of chemicals
– Partnership with the Helmholtz Center Berlin to develop photoelectrochemical solar reactors
– Demonstrations at above the 100 kW_{th} range
– Assessment and optimisation of the technologies on a system level, techno-economic analysis and transfer of the results to industry
– Analysis of heat transfer fluids; especially mineral oils, silicone oils, and molten salts

Qualification

R&D objectives

KONTAS rotating platform for performance testing of components at PSA.

The department facilitates cost reduction by providing measurement data to optimise O&M, improve performance and durability, and adapt to on-site meteorological conditions.

Specific R&D objectives:
– Develop test procedures and instruments for quality assessment
– Providing data on performance of CSP components and systems measured in laboratory and field
– Investigate effectiveness of measures for water saving
– Assess durability of advanced components
– Measurement of the weather influence on the performance of plants
– Develop measurement techniques for district and building energy analysis

Structure of the department

OPAC Mirror Laboratory.

The department has a staff of 33 in 4 teams between Almeria, Cologne and Jülich:
– **Components** (Dr.-Ing. Björn Schiricke, 9 members)
Provision of test benches for component qualification and measurement systems. In the QUARZ® Center in Cologne and at PSA we test mirrors, receivers, flexible connectors for PT and tracking systems. Additionally, this group develops measurement systems to analyse district and building energy efficiency.
– **Systems** (Dr.-Ing. Marc Röger, 14 members)
Development and application of measurement techniques to evaluate and optimise CSP technology systemwide. This includes both the optical qualification of solar fields and the thermal characterisation of receiver systems for solar tower and parabolic trough plants.
– **Durability** (Dr.-Ing. Florian Sutter, 3 members)
Durability testing of key components. Mirrors are exposed outdoors in different climates and accelerated ageing methods in the lab are developed to reproduce degradation in the field. Absorber coatings are tested under concentrated radiation.
– **Meteorology** (Dr. Stefan Wilbert, 6 members)
Measuring meteorological conditions and all relevant parameters for plant development and operation. The team operates a well-equipped meteorological station and several nowcasting systems in PSA and commercial plants and a sensor/camera network with cloud cameras in Oldenburg/Germany.

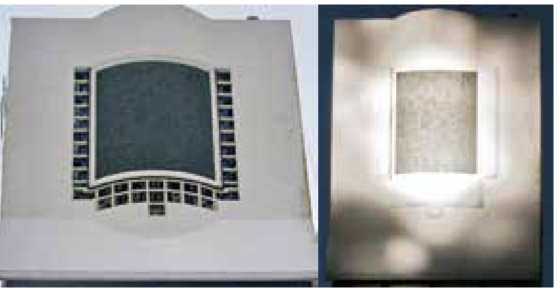
Main competencies

Dr.-Ing. Peter Heller
Head of Department

– Develop test procedures, measurement standards and certification for key components' performance and durability in laboratory and field
– Develop methods for accelerated ageing of components for fast prediction of lifetime degradation
– Provide meteorological data to support implementation at suitable sites and to optimise O&M
– Develop measurement systems to analyse energy use in buildings and districts
– Develop models for performance analysis based on measurement data

Jülich Solar Tower Test Facilities

DLR purchased the Jülich Solar Tower in 2011, two years after its start-up. The facility is unique in Germany. Now the institute not only operates and optimises this experimental solarthermal power plant, but also develops measurement techniques for solar tower CSP, and tests innovative receiver technologies at a scale of up to 1 MW.



Installation of receiver return air nozzles (left) and solar test after completion (right), 2015.

At Jülich 2,000 heliostats, with a total surface of approximately 18,000 m² focus the sunlight up to the solar receiver at the top of the 60-metre-high tower. The receiver with an area of 22 m² is composed of porous ceramic elements. Ambient air flows through this porous receiver. The air is heated up to around 700°C and transfers its energy to a full water-steam cycle and a generator able to feed up to 1.5 MW into the medium-voltage grid. An integrated storage facility can hold the heat for more than one hour of full-load operation.

Many different modifications have been added to the system, including hot air valves to reduce convection losses inside the heat storage and hot air piping, optimised return air nozzles at the receiver to raise air return ratio and lower pressure losses, a test of operational assistance systems connected to the process control system, and a live test of aim point optimisation systems to improve receiver performance. Also several measurement technologies for large-scale systems have been developed, including return air measurement based on induced helium detection in the hot air flow, and flux density measurement at the receiver surface without moving bars or other error-prone devices.

A level, halfway up the solar tower, is equipped for test installations. Since 2012 different test setups have been installed for open volumetric receivers, a particle receiver and solar chemical applications, for example a sulfur cycle as part of a high temperature electrolysis. High demand for large-scale tests and the availability of only one test platform has created a bottleneck, so in May 2019 we started building the Multifocal Tower.

Felix Göhring
Team Leader

Multifocal Tower

This second tower will be finished in spring 2020, with three new test platforms. Receivers up to 2 MW_{th} can be tested there. The first two receiver test systems will be installed beginning in summer 2020. The lowest platform will hold a molten salt receiver system and the highest platform a particle receiver. The mid platform is designed for solar chemical applications, for example up to eight different technical gases can be used here for chemical reactors.

Multifocal Tower - plan (left) and actual construction state in October 2019 (right).

Solar Furnace and High-Flux Solar Simulator

The institute's high-flux solar furnace has been in operation since 1994. It is ans important tool to develop high temperature solar technologies by using real concentrated sunlight. More than 250 test campaigns have built excellent experience in high-flux solar radiation unparalleled in Germany.

The solar furnace concentrates sunlight up to 5 MW/m² and achieves temperatures up to and even above 2500°C. Sunlight is reflected onto a concentrator by a flat mirror (heliostat). The concentrator reflects the radiation so the focus is outside the axis of the incident light, but inside the laboratory building where the experiments are located. The incident concentrated radiation can be controlled with an aperture (shutter). This referred off-axis-geometry provides the advantages of non-moving focus in relation to the current sun position, while the test setup is not shadowed by the incident radiation.

When solar irradiation is low, the high-flux solar simulator (HFSS) complements the solar furnace with artificial light, based on elliptic reflectors with xenon short-arc lamps. Since it is not dependent on on-sun irradiation, the HFSS enables long-term experiments and certification-level component testing. The radiant energy can reach a power density up to 4 MW/m².

Both the HFSS and the on-sun facilities can achieve beam power up to 25 kW. In both, the operator can use especially manufactured components like tilted mirrors, beam guidance systems, various aperture shapes or different vacuum chambers. The measurement systems and infrastructure are internationally unparalleled. The facilities are indispensable for the development from laboratory to full-scale applications.

Prof. Dr. Christian Sattler
Head of Department

The HFSS and solar furnace are primarily intended for testing processes to generate solar fuels, chemical components for storage, and applications in chemical, technical and metallurgical high-temperature processes. An area of interest is the testing of various materials under extreme conditions as well as concentrated solar radiation, such as high vacuum down to 10^{-6} mbar. Here the solar furnace bridges DLR's Solar Research with its Space Research. The simulation of radiation in space is a key competence that can be used to qualify components for satellites as well as for the sintering of extraterrestrial material to produce bricks for settlements on the moon or other planets. Both facilities are open for public use.

Solar furnace at DLR's main site in Cologne.

Synlight®

Synlight®, the world's largest solar simulator is located at our site in Jülich. It was inaugurated on 23 March 2017. The focus of Synlight® is the development of production processes for solar fuels. In addition, researchers and industrial partners in the solar thermal power plant or aerospace industries will find ideal conditions for tests of full-size components. Each of its 149 Xenon short-arc lamps has the output of a large cinema projector. Together, they produce a light intensity that corresponds to more than 10,000 times the incident solar radiation on Earth's surface.

Synlight® has three independent test chambers. Its novel modular design is unique in using individually adjustable Xenon short-arc lamps. These enable solar radiation powers of up to 380 kilowatts in the central chamber and up to 240 kilowatts in the side chambers. A maximum flux density of more than 11 megawatts per square meter can be achieved. At this scale, Synlight® fills the gap between laboratory systems like DLR's solar furnace in Cologne and large scale technical facilities like DLR's solar tower in Jülich, for developing and qualifying solar thermal components and processes. No other installation worldwide offers these capacities.

Two test chambers are specially designed to meet the requirements of solar-chemical process development testing and offer direct access to gas scrubbers and neutralisers – a prerequisite for testing processes for the production of solar fuels. Shutters – four meters in width and height – and the room heights of five meters make it possible to irradiate large elements, such as spaceflight components. A fundamental feature of Synlight® is its multi-focus capability, which enables the available amount of artificial solar irradiation to be used for either one large application or split among a number of small ones.

Prof. Dr. Christian Sattler
Head of Department

The facility is open for public use. Specialists from the institute assist users in the preparation and execution of their experiments. After only two years the facility is already well established in the global community. It is fully booked not only by DLR users but also by companies and research partners. Additional radiation facilities are installed on the ground floor of Synlight® to make even four parallel experiments possible. Synlight® is part of the European SFERA III project which provides the access to large scale research infrastructures.

Plataforma Solar de Almería (CIEMAT)

DLR has been co-operating with its partner CIEMAT since the creation of the Plataforma Solar de Almería. Our institute employs a permanent staff of around 25 scientists and engineers in Almería, cooperating with their Spanish colleagues on a project-by-project basis. The most important joint research facilities are:

REPA test bench to test flexible connections for parabolic troughs.

The mirror laboratory OPAC is focused on the characterisation of the reflectance and the durability of mirrors. OPAC allows all relevant durability tests of mirrors, such as damp heat and condensation, salt spray, UV/humidity, thermal cycling and industrial environment exposure. PSA also has equipment to perform abrasion tests of glass envelopes or anti-soiling coatings as well as sand erosion tests. Outdoor exposition of mirror samples to the Tabernas desert environment allows us to compare natural degradation with laboratory results.

The PROMETEO facility is a loop of two 100 m parabolic trough collectors with an aperture of 7.5 m each, connected to a BOP. The facility had been adapted for the testing of an innovative silicone-oil based HTF which allows operation temperatures of up to 430°C.

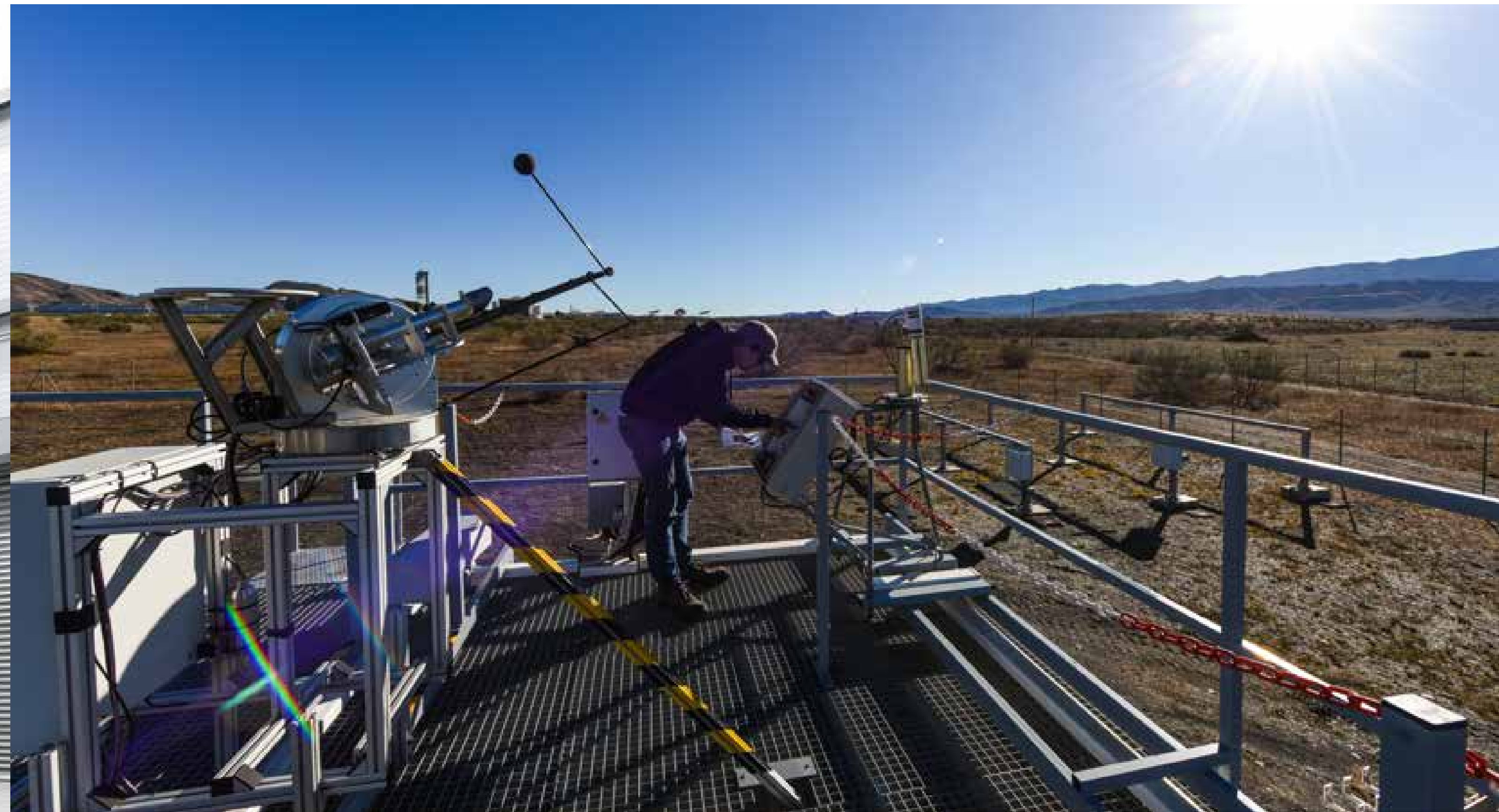
The REPA test bench allows for testing of two flexible hoses at a time at temperatures up to 430°C. Silicone oil is used as HTF. The connectors are exposed to representative mechanical and thermal stress found in commercial plants to test durability for a lifetime of 20 plus years.

The rotating parabolic trough platform KONTAS is designed for performance assessment of a complete collector module. It is equipped with a heating/cooling unit and a temperature control. The platform can be oriented or tracked according the parameters to be analysed, for example, the Incidence Angle Modifier (IAM). There is industry demand for detailed analysis of prototype mirrors and absorbers. KONTAS is also used to compare various test bench laboratory results with field data.

Dr.-Ing. Peter Heller
Head of Department

The meteorological station METAS consists of a unique set of instruments for measuring all the parameters relevant to solar energy systems. Besides solar radiometers and a corresponding calibration facility, also, aerosol measurements can be carried out continuously with a sun photometer, particle counters and visibility sensors. The soiling effect is measured with various techniques. Clouds are monitored with all sky imagers and LIDAR systems.

Meteorological station METAS.



QUARZ® Test and Qualification Center for CSP Technologies

Deflectometric shape measurement of mirror facet.

The QUARZ® Test and Qualification Center was originally built in 2009 in answer to the growing industry need for quality assessment of CSP components developed for the booming Spanish market. Today the QUARZ® Center provides detailed measurement reports used by the CSP industry to demonstrate and validate the quality of their products in negotiations with EPC companies.

The performance of newly developed components like mirrors or receivers for parabolic trough plants can be tested to detect and correct weaknesses. In addition to measuring current component performance, the industry also needs to know their durability over a 20 plus year lifetime. EPC companies find the measurement systems at the center useful to get an accurate picture of how products measure up against each other in the market.

To be able to provide these capabilities, the institute's scientists had to develop the necessary measurement methodologies and instruments.

Since the QUARZ® Center's beginnings we have cooperated with other national and international research institutes to compare measurement procedures and work to harmonise and standardise the measurements.

Development of testing methodologies and procedures

In our quality tests we measure optical properties such as reflectivity and absorptivity, geometrical properties such as shape accuracy and tracking precision, mechanical properties such as torsion stiffness, and thermal losses.

The measurement procedures simulate load and real-life operation in a commercial CSP power plant. Our goal is to obtain comparability of components and an assessment of their influence on the total efficiency of the power plant, based on consistent quality criteria. Our methods and devices for testing are continuously optimised, based on our test results and the development of components in the industry.

Dr.-Ing. Peter Heller
Head of Department

Dr.-Ing. Björn Schiricke
Team Leader

Development of standards for testing of components

By way of developing international testing standards, which had not previously existed for the CSP industry, we used the knowledge gained during testing and evaluation to define the best suited parameters, discussed these with industry and other researchers after conducting round robin campaigns and provided SolarPACES guidelines for measurements which were introduced to the standards organisations, such as DIN, AENOR and IEC. We actively participate in the working groups at AENOR and IEC.

Part of test bench to measure the optical efficiency of parabolic trough receivers.

Évora Molten Salt Platform

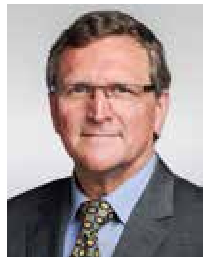
DLR and the University of Évora (UÉ, Portugal) jointly develop and operate the Évora Molten Salt Platform (EMSP) under a bilateral agreement signed in 2015. The installation is based on previous work by Siemens, which had built major components before exiting the CSP industry and the EMSP project in Portugal. The Institute of Solar Research initiated the transfer of existing equipment from Siemens to the site owner UÉ, and formed a new consortium with industry and the Renewable Energies Chair of UÉ to adapt and complete the test facility. This ongoing work is nearing completion.

The plant reproduces the behavior of each of the solar components in a parabolic trough CSP plant (except for the conventional power block) to demonstrate safe, reliable and efficient operation. Aiming to allay concerns over molten salt in parabolic trough systems, the design allows us to:

- Validate procedures to prevent salt freezing, for filling and draining of the plant, black-out scenarios, and to resolve blockages caused by freezing,
- Investigate material wear and tear due to corrosion and thermal cycling, thermal stability and ageing of salt mixtures,
- Prove reliability of critical components like flexible connections and the molten salt/once-through steam generating system,
- Evaluate performance of the collector system and the energy requirements for anti-freeze operation.

Technical description of the plant

EMSP comprises a solar field, salt system with storage, steam generator and water/steam cycle, control system and auxiliaries. The solar field consists of one loop of Helio Trough® 2.0 large aperture parabolic trough collectors, adapted to operation with molten salt up to 560°C. It has a nominal power of about 2.7 MW_{th}. The collectors are installed in two rows with a length of 360 meters each. The salt system comprises a hot and a cold storage tank, a drainage tank below ground level including a salt melting unit, and pumps and valves to control the different modes of operation. The steam generator has a capacity of 1.6 MW_{th} at 140 bar/560°C. Turbine operation is simulated by pressure and temperature reducing stations and an air-cooled condenser in the water/steam system.



Klaus Hennecke
Project Manager

A versatile test facility for testing CSP and emerging technologies

The EMSP allows us to investigate and validate a great variety of innovations in a relevant environment. Beyond the original operation purpose, the investigation of molten salt as the heat transfer and storage medium, we can also test emerging applications, for example Carnot batteries that could provide grid stabilising services through thermal storage. The first test campaign with molten salt is scheduled for summer 2020, with a project pipeline already reaching into 2022.

EMSP aerial view.

Recognitions and Awards

2019
- **Institute of Solar Research together with DLR spin-off CSP Services GmbH:** CSP Plaza Technology Innovation Award for "QFly: Airborne Measurement of CSP Solar Fields"
- **Josua Vieten:** Helmholtz Doctoral Student Award 2019, Research Area Energy
- **Sebastian Richter, Stefan Brendelberger, Felix Gersdorf, Tobias Oschmann, Christian Sattler:** First place Best Paper Award 2019 ASME 13th International Conference on Energy Sustainability
- **Ana Carolina do Amaral Burghi:** Young Scientist Award of the 2019 International Conference of Energy and Meteorology

2018
- **Josua Vieten:** Doctoral student price of the Germany Foundation Energy & Climate Protection
- **DLR Institute of Solar Research (Team: Christoph Prahl, Marc Röger, Nils Algner, Steffen Ulmer):** SolarPACES Technology Award 2018 for QFly, an airborne system for the quality assessment of solar thermal power plants
- **Jan-Peter Säck:** DLR-Award Integrated Management System
- **Silvan Siegrist (first place), Pascal Kuhn (second place):** DLR-Wettbewerb der Visionen
- **Marc Röger:** Awarded as "DLR-Senior-Wissenschaftler" (DLR Senior Scientist)

2017
- **Robert Pitz-Paal:** Farrington Daniels Award of the International Solar Energy Society ISES
- **Christian Sattler:** ASME Fellow

2016
- **Christian Sattler:** ASME Yellott Award

2015
- **Team 24/7 (now DLR Spin-Off HelioHeat) Lars Amsbeck, Eckhard Lüpfert, Tobias Prosinĕcki:** First place in the NUK-Businessplan Competition. (NUK – Neues Unternehmertum Rheinland, a Cologne network supporting start-ups)
- **Friedemann Call:** Hugo-Denkmeier-Preis DLR
- **Nicolas Bayer-Botero, Dennis Thomey, Alejandro Guerra-Niehoff, Christian Sattler, Robert Pitz-Paal;** Best Paper Award, 6th International Conference on Hydrogen Production
- **Stefan Wilbert:** Borchers-Plakette RWTH Aachen

2014
- **DLR-Institute für Solarforschung, Technische Thermodynamik, Verbrennungstechnik und Werkstoffforschung:** Auszeichnung DLR-Center of Excellence
- **Nicole Janotte:** Borchers-Plakette RWTH Aachen;
- **Stefan Wilbert, Norbert Geuder:** SolarPACES Technology Award for the Advanced Solar Resource Assessment with Rotating Shadowband Irradiometers
- **Nicola Bayer Botero, Alejandro Guerra Niehoff, Dennis Thomey, Martin Roeb, Christian Sattler:** WHEC Award for Exceptional Oral Presentation
- **Friedemann Call, Jan Felinks, Matthias Lange:** DLR-Wettbewerb der Visionen

2013
- **Stefan Brendelberger:** MatSEEC poster price

2012
- **Martina Neises:** Friedrich-Wilhelm-Preis RWTH Aachen
- **Siw Meiser:** Best Paper Award ASME Conference
- **Fabian Wolferstetter, Klaus Pottler, Ahmed Alami Merrouni, Ahmed Maezrhab and Robert Pitz-Paal:** Desertec Best Paper Award for the article "A Novel method for Automatic Real-Time Monitoring of Mirror Soiling Rates." Paper read at SolarPACES Conference, at Marrakesh, Morocco
- **Spin-Off CSP Services GmbH:** Finalist of "Deutscher Gründerpreis, Kategorie Aufsteiger" (German Founder's Price, category newcomer)

2011
- **Martina Neises:** "100 Frauen von Morgen" (100 Women of Tomorrow), an award of the initiative "Deutschland – Land der Ideen" (Germany - Country of Ideas)
- **Fabian Lennart:** Year Award of VDI Niederrhein (Association of German Engineers, Section Lower Rhine)
- **Institute of Solar Research, Jülich Solar Tower:** Award "Ort des Fortschritts" (Site of Innovation), by the government of North Rhine-Westphalia

Selection of Relevant Publications and Patents According to Research Highlights

Seamless Flow – Solar Steam Generation in Line Focus Systems

- **Hoffmann, A. et al., (2018)** Application of a single wire-mesh sensor in a parabolic trough facility with direct steam generation. Solar Energy, (159). pp. 1016-1030.
- **Willwerth, L. et al., (2018)** Experience of operating a solar parabolic trough direct steam generation power plant with superheating. Solar Energy, (171), pp. 310-319.
- **Hoffmann, A. et al., (2016)** Numerical investigation of severe slugging under conditions of a parabolic trough power plant with direct steam generation. Solar Energy, (133), pp. 567-585.
- **Feldhoff, J.F, et al., (2015)** Transient models and characteristics of once-through line focus Systems. Energy Procedia, (69), pp. 626-637.
- **Khenissi, A. et al., (2015)** Return of experience on transient behavior at the DSG solar thermal Power plant in Kanchanaburi, Thailand. Energy Procedia, (69), pp. 1603-1612.
- **Schenk, H. et al., (2015)** SolSteam - Innovative integration concepts for solar-fossil hybrid process steam generation. Energy Procedia, (69), p. 1676-1687.
- **Schenk, H. et al., (2014)** Energetic Comparison of Linear Fresnel and Parabolic Trough Collector Systems. Journal of Solar Energy Engineering, (136), pp. 041015-1 - 041015-11.
- **Hirsch, T. et al., (2013)** Advancements in the field of direct steam generation in linear solar concentrators - A review. Heat Transfer Engineering, (27) pp. 258-271.
- **Feldhoff, J. F. et al., (2012)** Comparative system analysis of direct steam generation and synthetic oil parabolic trough power plants with integrated thermal storage. Solar Energy, (86), pp 520-530.
- **Hirsch, T. et al., (2007)** Dynamics and control of parabolic trough collector loops with direct steam generation. Solar Energy, (81), pp. 268-279.

- **Patent DE 10 2012 111775** Stabilization of steam fraction in DSG plants by means of a passiv component.
- **Patent EP 2 454 523 B1** Control scheme for stabilizing the endpoint of evaporation
- **Patent DE 10 2009 047 204 B9** Operation of DSG solar field at reduced irradiation
- **Patent DE 10 2012 103 457** Cascaded defocusing control for DSG plants
- **Patent DE 10 2007 005 562** Temperature control for the DSG superheating section.
- **Patent DE 10 2007 052 234** Mass flow control in the DSG evaporator section

Rolling Stones – Direct Absorption Particle Receiver Technology

- **Ebert, M. et al., (2019)** Operational Experience of a Centrifugal Particle Receiver Prototype. AIP Conference Proceedings, 2126 (030018), SolarPACES 2018, 2.-5. Oct. 2018, Casablanca, Morocco. DOI: 10.1063/1.5117530.
- **Galiullin, T. et al., (2019)** High temperature oxidation and erosion of candidate materials for particle receivers of concentrated solar power tower systems. Solar Energy, (188), pp. 883-889. DOI: 10.1016/j.solener.2019.06.057.
- **Amsbeck, L. et al., (2018)** First tests of a centrifugal particle receiver with a 1m² aperture. In: AIP Conference Proceedings, 2033 (040004), SolarPACES 2017, 26.-29. Sept. 2017, Santiago de Chile. DOI: 10.1063/1.5067040.
- **Ebert, M. et al., (2016)** Upscaling, Manufacturing and Test of a Centrifugal Particle Receiver. ASME Energy Sustainability Conference, 26.-30. June 2016, Charlotte, United States.
- **Wu, W. et al., (2015)** Prototype Testing of a Centrifugal Particle Receiver for High-Temperature Concentrating Solar Applications. Journal of Solar Energy Engineering, 137 (041011). DOI: 10.1115/1.4030657.
- **Gobereit, B. et al.; (2015)** Assessment of a Falling Solid Particle Receiver with Numerical Simulation. Solar Energy, (115), pp. 505-517. DOI: 10.1016/j.solener.2015.03.013.

- **Patent DE 10 2010 025 602.1** Face-Down Receiver

More than just Hot Air – Open Volumetric Receiver Technology

- **Stadler, H. et al., (2019)** CFD model for the performance estimation of open volumetric receivers and comparison with experimental data. Solar Energy, pp. 634-641.
- **Stadler, H. et al., (2019)** Performance assessment of an improved open volumetric receiver design with 240 MWth. AIP Conference Proceedings, 2126 (030057). doi: 10.1063/1.5117569.
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– **Ahlbrink, N. et al., (2013)** Optimization of the Mass Flow Rate Distribution of an Open Volumetric Air Receiver. Journal of Solar Energy Engineering, 135 (041003).
– **Koll, G. et al., (2009)** The Solar Tower Jülich - A Research and Demonstration Plant for Central Receiver Systems. Paper presented at the SolarPACES 2009, Berlin.
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– **Fend, T. et al., (2004)** Porous Materials as Open Volumetric Solar Receivers: Experimental Determination of Thermophysical and Heat Transfer Properties. Energy, (29), pp. 823-834.
– **Téllez, F. et al., (2004)** Thermal Performance of SolAir 3000 kWth Ceramic Volumetric Solar Receiver. Paper presented at the 12th International Symposium Solar Power and Chemical Energy Systems, Oaxaca, Mexico.
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– **Patent DE 10 2013 221 884** Receiver for solar energy generation
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– **Patent DE 10 2016 203 102** Receiver for solar energy generation
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– **Uhlig, R. et al., (2019)** Using Corrugated Tubes in External Molten Salt Receivers. In: AIP Conference Proceedings, 2126 (030061). SolarPACES 2018, 2.-5. Oct. 2018, Casablanca, Morocco. DOI: 10.1063/1.5117573.
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– **Patent EP 000002047182 B1** Closed loop heliostat control system

Good Bye Oil – Solar Production of Fuels and Commodities

– **Moumin, G. et al., (2019)** Solar treatment of cohesive particles in a directly irradiated rotary kiln. Solar Energy, (182) pp. 480-490.

– **Patent DE 10 2016 209 817** Solarbeheizter Reaktor, Industrieofen sowie Zementherstellungsanlange
– **Patent DE 10 2016 209 823** Solarbeheizter Reaktor, Industrieofen sowie Zementherstellungsanlange
– **Patent DE 10 2017 219 374** Solarreceiver sowie Verfahren zum Betrieb eines Solarreceivers

One Model Fits All? Simulation Tool for Solar Power Plants

– **Dersch, J. et al., (2019)** Impact of DNI Nowcasting on Annual Revenues of CSP plants for a time of delivery based feed in tariff. Meteorologische Zeitschrift, (28), pp. 235-253.
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– **Noureldin, K., et al., (2018)** Modelling an automatic controller for parabolic trough solar fields under realistic weather conditions. AIP Conference Proceedings, 2033 (210009).
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- **Patent ES P201231143** Procedimiento para la determinación de la intensidad de la radiación circunsolar
- **Patent DE 10 2017 211 466** Verfahren zur Bestimmung des Verschmutzungsgrades einer reflektierenden Fläche eines Solarkraftwerks

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HELITEP – Testing Platform for Heliostat Qualification

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- **Hilgert, C. et al., (2019)** Qualification of silicone based HTF for parabolic trough collector applications. AIP Conference Proceedings, 2126 (080003), doi: 10.1063/1.5117598
- **Jung, C. et al., (2015)** Technological perspectives of silicone heat transfer fluids for concentrated solar power. Energy Procedia, (69), pp. 663-671.

The Key to Hydrogen? Perovskites for Solar Thermochemical Water Splitting

- **Vieten, J. et al., (2019)** Materials design of perovskite solid solutions for thermochemical applications. Energy & Environmental Science, (12), pp. 1369-1384.
- **Vieten, J. et al., (2019)** Redox behavior of solid solutions in the $SrFe_{1-x}Cu_xO_{3-\delta}$ system for application in thermochemical oxygen storage and air separation. Energy Technology, (7), pp. 131-139.
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Black is Black? Absorbing Solar Flux for a Lifetime

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- **Caron, S. et. al., (2019)** Forty Shades of Black: a Benchmark of High Temperature Sprayable Black Coatings Applied on Haynes 230. Paper presented at SolarPACES Conference, Daegu, South Korea.
- **Caron, S. et. al., (2018)** Accelerated ageing of solar receiver coatings: Experimental results for T91 and VM12 steel substrates. AIP Conference Proceedings, 2033 (230002), doi: 10.1063/1.5067230

8. List of Acronyms and Abbreviations

ABO2.5	Brownmillerite
ABO3	Perovskite
ALFRED	Artificial Learning Flexible Renewable Energy Dispatch
AR	Anti-Reflective
BOP	Balance of Plant
CCD	Charge-Coupled Device
CentRec®	Centrifugal Particle Receiver
CeraStorE	Ceramic Storage Energy – research center for ceramic materials and thermal storage technology
CFD	Computational Fluid Dynamics
CHP	Combined Heat and Power
CFD	Computational Fluid Dynamics
CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas – Research Centre on Energy, Environment and Technology
CSH	Concentrated Solar Heat
CSP	Concentrated Solar Power
CST	Concentrating Solar Thermal
DCSP	Deutsches Industrienetzwerk Concentrated Solar Power e.V. – German Association for Concentrated Solar Power
DISS	Direct Solar Steam
DEM	Discrete Element Method
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V. – German Aerospace Center
DNI	Direct Normal Irradiation
DSG	Direct Steam Generation
EMSP	Évora Molten Salt Platform
EPC	Engineering, Procurement and Construction
ESTELA	European Solar Thermal Electricity Association
FEM	Finite Elements Method
HeliTeP	Heliostat Test Platform
HFSS	High-Flux Solar Simulator
HiTRec	High Temperature Receiver
HTF	Heat Transfer Fluid
IAM	Incidence Angle Modifier
IEA	International Energy Agency
KONTAS	Konzentrator-Teststand Almeria Spanien – on-sun test bench for parabolic trough collectors
LCOE	Levelized Cost of Electricity
METAS	Meteorological station for solar energy Applications
MPC	Model Predictive Controller
Nd:YAG	Neodymium-doped Yttrium Aluminum Garnet
NRW	North Rhine-Westphalia
O&M	Operations and maintenance
OPAC	Optical Ageing Characterization laboratory
OpenFOAM	Open-source Field Operation And Manipulation C++ modelling for continuum mechanics
OPEX	Operating expenses
PID	Proportional Integral Derivative
PIV	Particle Image Velocimetry
PPA	Power Purchase Agreement
PSA	Plataforma Solar de Almería
PV	Photovoltaic
QFly	Qualification Flying – drone system for aerial monitoring of solar fields
QUARZ®	Test- und Qualifizierungszentrum für konzentrierende Solartechnik – Test and Qualification Center for CSP Technologies
REPA	Rotation and Expansion Performing Assemblies – ball joints and flex hoses, etc.
R&D	Research and development
RSI	Rotating Shadowband Irradiometer
Si-HTFs	Silicone-based Heat Transfer Fluids
SKT	Solare Kraftwerkstechnik - solar power plant technology division
SolarPACES	Solar Power and Chemical Energy Systems
STJ	Solar Tower Jülich
Synlight®	Synthetic Light – the world's largest simulated sunlight testing center for solar
UAE	United Arab Emirates
UAV	Unmanned Aerial Vehicle
WobaS	Wolkenkamera-basierte Betriebsstrategien für Solarkraftwerke – cloud camera
WWR	Window-Wall-Ration
α	Absorptance
ε	Emittance
σ	Standard deviation
ΔH	Enthalpy change
ΔS	Entropy change
ΔG	Gibbs energy

Imprint

Publisher:
German Aerospace Center (DLR)
Institute of Solar Research

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Design and Print:
Hacker Media, Amselweg 10, 71384 Weinstadt
Printed on environmentally friendly, chlorine-free bleached paper.

Date:
Cologne, December 2019

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About DLR

DLR is the Federal Republic of Germany's research centre for aeronautics and space. The organisation also completes research in the areas of energy, transport, security and digitalisation. Acting on behalf of the federal government, the DLR Space Administration designs and implements Germany's space programme, together with national and international partners. DLR is also the umbrella organisation for two project management agencies that promote research.

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German Aerospace Center

Supported by:
Federal Ministry for Economic Affairs and Energy
on the basis of a decision by the German Bundestag