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Umwelt, Verkehr, Energie und Kommunikation UVEK
Bundesamt für Energie BFE

Jahresbericht 2. Dezember 2011

Solar Production of Zinc and Hydrogen – Reactor Optimisation for Scale-up (1)

and

Towards Industrial Solar Production of Zinc and Hydrogen – 100 kW Solar Pilot Reactor for ZnO Dissociation (2)

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Contents

Abstract

A 100 kW pilot plant for the solar thermal dissociation of ZnO was designed and fabricated at *PSI*. A first experimental campaign of six weeks was scheduled and conducted in June/July 2011 at the 1 MW Solar Furnace (MWSF) in Odeillo, France. More than 60 hours of on-sun testing in the MWSF were recorded, each experiment lasting between three and seven hours. All systems of the solar pilot plant have been tested and qualified. Valuable operational experience was gathered and will help to further improve the current design for the second experimental campaign planned for 2012. It aims at optimizing the reactor performance by implementing a modified quench unit and by operating the reactor at higher temperatures using improved high-temperature wall materials. The goal will be to reach a Zn yield exceeding 50 % and a solar-to-chemical energy conversion efficiency approaching 10 %. The results from this research will extent the ability to store solar energy as a fuel – such as Zn, H_2, or syngas – in a manner that increases the chances of having a sustainable solution to the current world problem of being dependent on a limited supply of fossil fuels.

Project Goals

Research on the “Solar Thermal Production of Zinc” is continued at *PSI*’s Solar Technology Laboratory with financial support of *BFE*. We present a status report on both the R&D project *Solar Production of Zinc and Hydrogen – Reactor Optimisation for Scale-Up* (2008-11) [1] and the P&D project *Towards Industrial Solar Production of Zinc and Hydrogen – 100 kW Solar Pilot Reactor for ZnO Dissociation* (2010-2011) [2]. A proposal for prolongation of the P&D project *Solar Production of Zinc and Hydrogen – 100 kW Solar Pilot Reactor for ZnO Dissociation* has been submitted to *BFE* [3].

The main purpose of the current research is to optimize the solar reactor technology for the thermal dissociation of ZnO at laboratory scale (solar power input of 10 kW) and to successfully demonstrate the fully integrated reactor at pilot scale (solar power input of 100 kW). Conceptual designs and preliminary economics for commercial solar Zn production and storage facilities based on large-scale concentrating solar power (CSP) tower technology will be developed.

The initial phase (“Optimization Phase”) of the R&D project encompasses the further development of a scalable and reliable 10 kW solar reactor prototype based on the existing solar chemical reactor concept previously designed and tested at *PSI*. The development work is focused on advancing the positive features of this concept and on optimizing the reactor’s operational parameters for maximum exergy efficiency. A major challenge is the design, fabrication and incorporation of a Zn/O_2 separation device, which is based on the rapid quenching of the Zn/O_2 mixture at the exit of the reactor cavity. Testing of the complete reactor/separator system at *PSI*’s Solar Research Facilities yields experimental data that are used – together with results from numerical models – to modify, as needed, the reactor concept to help ensure the successful scaling up to the pilot scale of 100 kW (“Pilot Phase”). The planned test site for the scale-up reactor is the 1 MW Solar Furnace (MWSF) at Odeillo, France.

The results from this research program will advance our ability to store solar energy as a fuel, such as Zn or H_2, in a manner that increases our chances of having a sustainable solution to the current world problem of being dependent on a limited supply of fossil fuels.

Goals for 2011. The following goals have been set for 2011:

- Until end of March 2011, the 100 kW pilot reactor and its peripherals will be fabricated at *PSI* (with major parts manufactured by small and medium Swiss companies).
- In April 2011, the solar reactor and the most critical components will be assembled and pre-tested at *PSI*. In May 2011, the complete pilot plant will be shipped to Odeillo, France.
- The first experimental campaign at the MWSF in Odeillo, France, is scheduled for June/July 2011. The main goal is reliable reactor operation without mechanical problems:
    - Aerodynamic window protection from condensing gases
    - Thermal shock resistant and chemically stable high-temperature materials
    - Efficient feeding of ZnO powder and removal of solid products
- For each experimental run, perform
    - Online measurement of O_2 in product stream to prove the successful dissociation of ZnO (Goal for 1st campaign: ZnO dissociation rate >8 kg/h)
    - Chemical analysis to determine the Zn content in the products (Goal for 1st campaign: Zn yield >50%)
    - Continuous temperature measurement at various positions in the reactor to validate the transient heat transfer model
    - Mass and energy balance to get information on the process development and the heat losses in the solar reactor
    - Solar-to-chemical energy conversion efficiency calculation (Goal for 1st campaign: $\eta > 5\%$)

Results

In 2011, the 100 kW pilot plant for the thermal dissociation of ZnO was fabricated and tested in a 1st experimental campaign at the MWSF in Odeillo, France. Initial operational experience with the scale-up reactor at a large-scale solar facility has been obtained. Preliminary experimental results have been presented at the SolarPACES Conference in Granada, Spain [4]. Currently, the 100 kW pilot plant is being refurbished and optimized at *PSI*. Design details of major components and the timetable for the 2nd experimental campaign in Odeillo are given below.

Solar reactor technology

The design of the 100 kW solar pilot reactor as depicted in Fig. 1 is based on previously investigated 10 kW reactor prototypes [5]-[7]. The hexagonal reactor shell is made of a 5 mm thick aluminum sheet to keep low the overall reactor weight. It consists of four divisible parts with the aim of allowing access to the reactor cavity and simplifying maintenance tasks: (1) The water-cooled front cone is attached to (2) the front cap, followed by (3) the center casing with the well-insulated cavity and (4) the rear panel containing the water-cooled quench unit. The total length of the reactor shell is 1327 mm and its minimum outer diameter is 1090 mm.

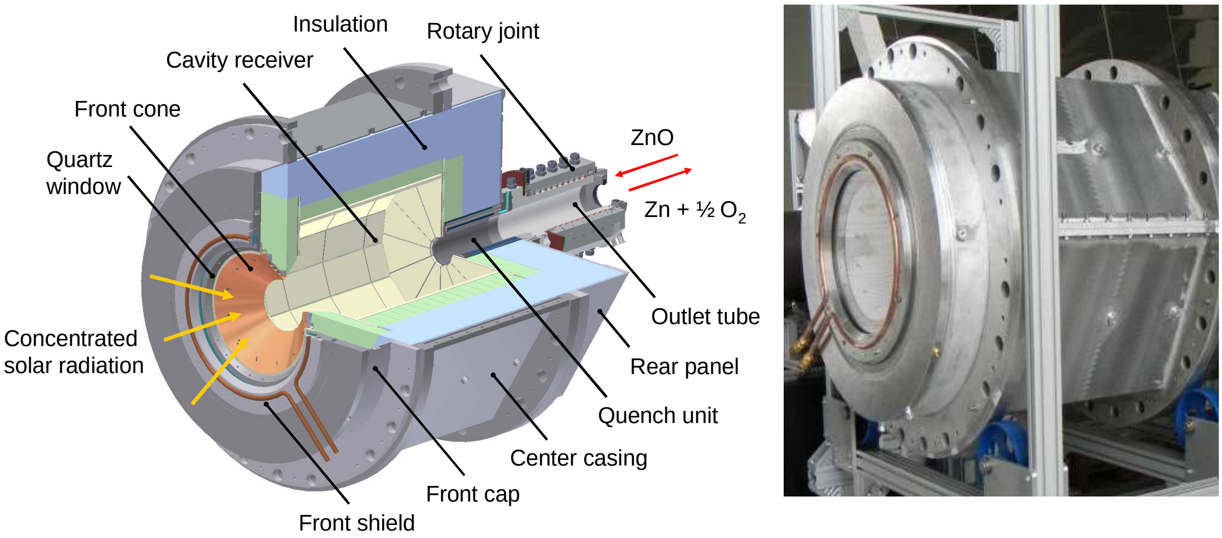


Figure 1: Schematic of the solar chemical reactor configuration [4] (left) and picture of the reactor showing the hexagonal aluminum shell (right).

The reactor cavity is lined with four layers of refractory ceramics (Insultech AG), shown in Fig. 2. The outermost layer (L4) is 20 mm thick porous insulation consisting of 69 % SiO_2 and 30 % SiC, followed by a 165 mm thick layer (L3) of alumina silicate fiber (55 % Al_2O_3, 40 % SiO_2, T_{max} = 1673 K) and a subsequent 50 mm thick layer (L2) made of 90 % Al_2O_3 and 8 % SiO_2 (T_{max} = 2073 K). The reactor assembly is finished with 12.7 mm thick sintered alumina tiles consisting of 99.5 % Al_20_3 (L1), hold in position with high temperature adhesive (Kerathin P1800, 84 % Al_2O_3, 16 % SiO_2, T_{max} =

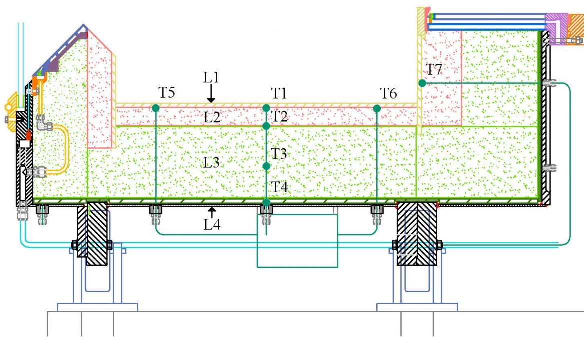


Figure 2: Schematic cross-sectional view of the lower part of the reactor with various thermocouples (T_i) and different insulation layers (L_i) indicated. From [4].

2073 K, Rath AG). This results in an inner cavity diameter of 580 mm and a length of 750 mm. The maximum cavity temperature is limited by the ZnO-Al_2O_3-SiO_2 eutectic phase melting temperature at around 1930 K [8].

Concentrated solar radiation is entering the cavity through a frustum-shaped (45°) front cone with an aperture diameter of 190 mm, as depicted in Fig. 3. The water-cooled copper cone is coated with a 1 mm thick ZrO_2 layer and finished with a 0.5 mm thick Al_2O_3 layer (Sulzer Metco Ltd.). This ceramic coating increases the cone surface temperature with the aim of avoiding undesirable condensation of product gases on its surface, introducing hot gas flows towards the quartz window. This transparent window with a diameter of 600 mm and a thickness of 12 mm closes the reactor from the surroundings and is hold in place by a water-cooled aluminum reactor front shield. To protect the window, an aerodynamic curtain is formed by injecting Ar through 24 radial nozzles at the window and 12 tangential nozzles embedded in the middle of the coated frustum-shaped cone (Fig. 3). The benefit of the Ar flow is two-fold: it reduces the Zn condensation on the window and acts as a carrier for the evolving gaseous products.

Figure 3: Frustum-shaped water-cooled front cone coated with ceramic ZrO_2/Al_2O_3 layer. To protect the window from precipitations, inert gas (Ar) is injected through 24 radial nozzles at the window and 12 tangential nozzles on the cone.

The outlet of the reactor cavity is an annular clearance in the center of the rear panel formed by a circular opening with a diameter of 105 mm and the ZnO particle feeder (Messag AG) with an outer tube diameter of 80 mm. The ZnO particles are fed from a container by a water-cooled conveyor screw, as shown in Fig. 4. During feeding, the conveyor screw moves horizontally into the cavity to distribute the ZnO powder along the bottom of the cavity. In the water-cooled quench unit, based on the concept presented in [7] and located at the outlet of the reactor cavity, up to 1500 l_N[1]/min of Ar can be added to the reacting gas flow coming from the cavity. The cold quench gas flow is injected through a circular ring gap with an angle of 10 degrees towards the flow to rapidly cool the reacting gas stream below the Zn melting point (693 K), thus favoring the formation of solid Zn particles and reducing the re-oxidation of Zn [9].

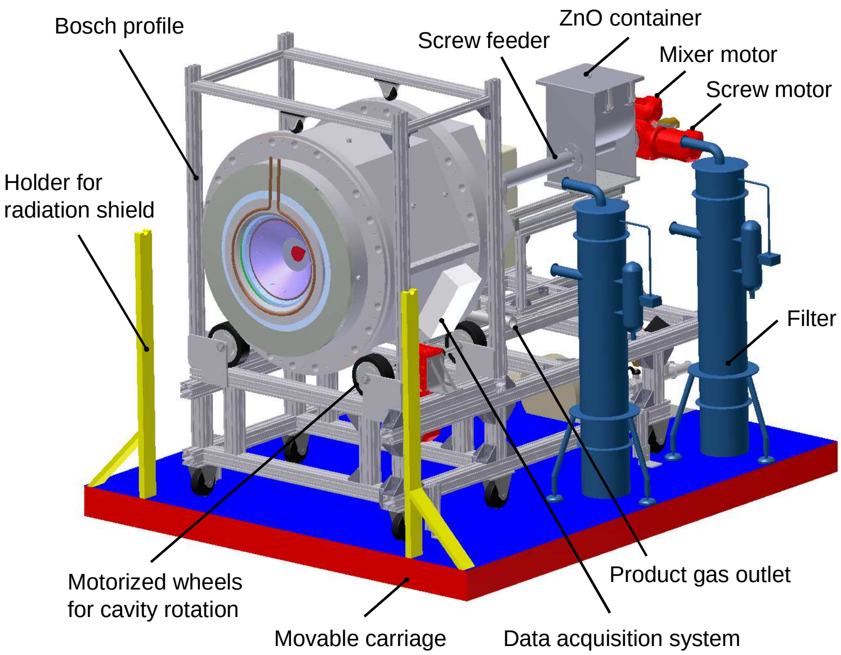


Figure 4: 3D schematic view of the 100 kW solar pilot plant mounted on the movable carriage, including the solar reactor, the dynamic screw feeder, and the filter system. From [4].

[1] l_N refers to liters at standard conditions: 273 K and 1 atm.

The 100 kW Solar Pilot Plant

Solar pilot plant layout

Figure 5 shows the final layout of the solar pilot plant. The process control system is running on a computer located in the control room of the MWSF, using hardware (real-time controller cRIO-9012) and software (Labview) from National Instruments. Three webcams are mounted on the tower platform to survey the solar pilot plant during operation. A high-resolution camera is placed opposite the solar tower at a distance of 18 m from the focal plane to continuously monitor the reactor front and the cavity. It is capable of recording in real time the evolution of vapor inside the cavity and any precipitations on the window, as well as incidents occurring during experimentation.

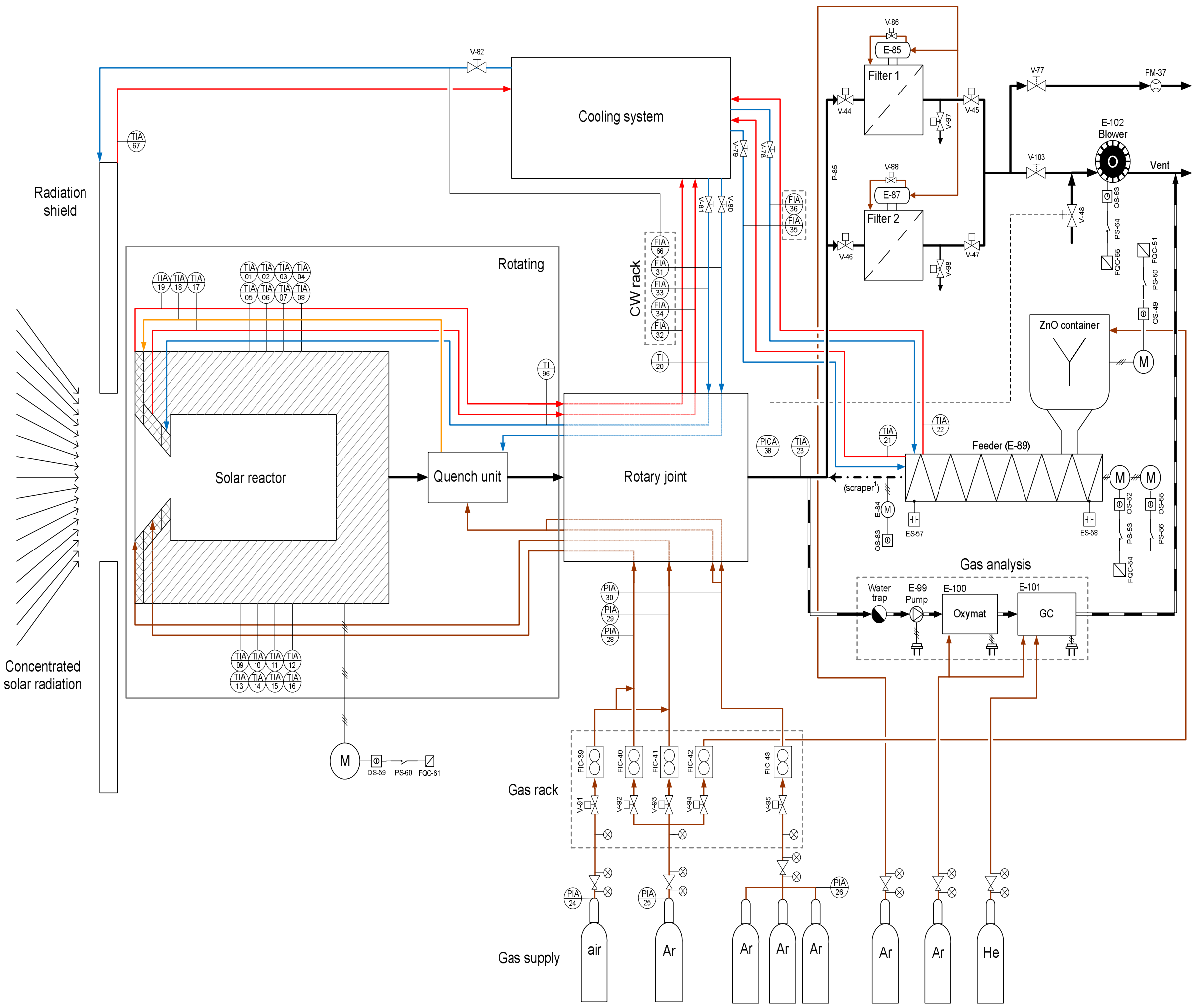


Figure 5: Piping and instrumentation diagram of the solar pilot plant including radiation shield, solar reactor, quench unit, rotary joint, ZnO dynamic feeder, filter system, pressure control, gas supply and storage, gas analysis, cooling water supply, water and gas piping, and location of temperature and pressure indication. From [4].

Gas supply – Gas supply (Ar, synthetic air) to the rotary reactor comprises the window and quench flows being fed through the rotary joint. A further gas stream is used to purge the ZnO container and the screw feeder. Gas flows are set using electronic mass flow controllers (Bronkhorst AG) mounted on the gas rack. Gas bottles and frames are stored outside the solar tower and connected to fixed gas supply lines.

Gas analysis – For the product gas analysis, a small gas flow (1.3 l_N/min) is extracted downstream the quench unit through a gas filter (HEPA, pore size 1.2 μm) into a gas chromatograph (Varian CP4900) to determine the exhaust gas composition. Gases including N_2, O_2, H_2, CO, CO_2, and CH_4 may be detected every two minutes approximately.

Particle filter – The filtering system (Hablützel AG, pore size 3 µm) separates solid particles from the exhaust gas, which ideally only contains Ar, low O_2 concentrations, and Zn particles. Switching between two filters (Fig. 4) using control valves (Valpes) allows collecting particles during the heat-up and cool-down phases separately from those produced at the desired operating temperature. The pressure inside the reactor is kept at 10 mbar (gauge) using a side channel blower (DutchAir) that is installed downstream the filter system. A slanted seat valve (Schubert&Salzer control systems) placed between the filter system and the side channel blower regulates the pressure by opening and closing towards the ambient and subsequently increasing or decreasing the gas flow from the reactor.

Data acquisition – Temperatures, pressure, inert gas and cooling water flows are acquired throughout the experimental run. Temperatures are measured with B-type (layer L2, Fig. 2) and K-type thermocouples (layers L3 and L4, Fig. 2) placed inside the solar reactor. Gas and cooling water temperatures are observed with Pt-100 temperature sensors.

Solar pilot plant fabrication, pre-assembling and pre-testing

Early in 2011, the main components of the 100 kW solar pilot plant – rotary reactor, rotary joint, and feeder – as well as auxiliary equipment such as particle filter, gas supply and cooling water systems were purchased and fabricated either at *PSI*'s workshop or at Swiss SMEs. Figure 6 presents a view of the rotary reactor (left), the rotary joint, the feeder tube, the ZnO container (right) and various auxiliary systems that are pre-assembled and mounted on the reactor support structure consisting of Bosch profiles that allow easy mounting and rapid modification of the experimental setup.

Feeding system – The screw conveyor within an aluminum tube can be horizontally displaced by 750 mm (Fig. 6). Attached is a 40 liter container that comprises a stirring device

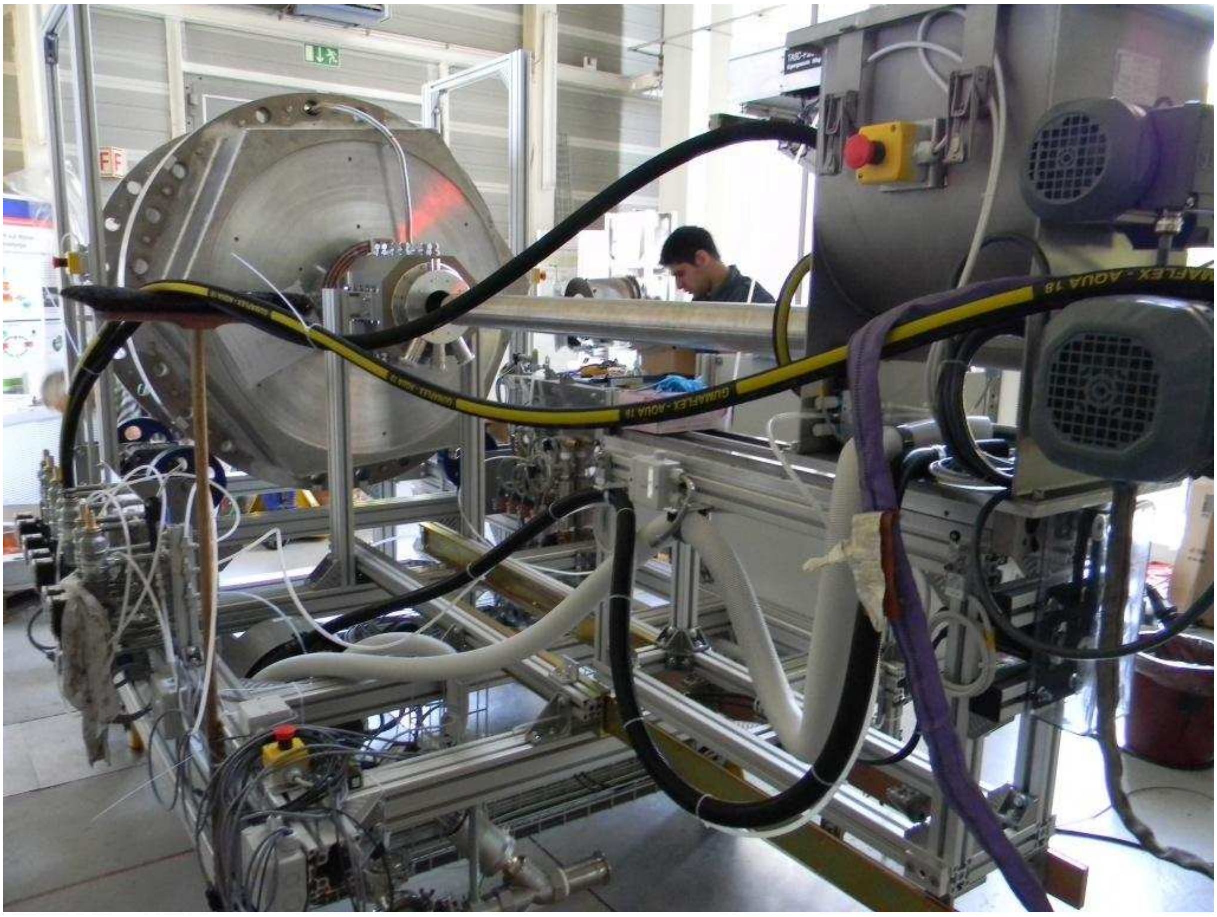


Figure 6: View of rotary reactor (left), rotary joint, screw conveyor tube, ZnO container (right) and various auxiliary systems pre-assembled and mounted on the reactor support structure consisting of Bosch profiles.

for charging the screw feeder with an accurate amount of ZnO. For long experimental runs, the container may be refilled with fresh ZnO powder.

Rotary joint – Figure 7a provides a close view of the rotary joint for transporting water and gas between the stationary and the rotating part of the reactor. An electric contact ring transmits power to and electrical signals from the data acquisition instruments (thermocouples and pressure transducers) mounted on the rotary reactor.

Cooling water system – Cooling water is provided by *PROMES-CNRS* and used for the large stationary radiation shield, the feeder with double jacket, the quench unit and the front cone (frustum), as well as the reactor front shield. The cooling water distribution panel is shown in Fig. 7b.

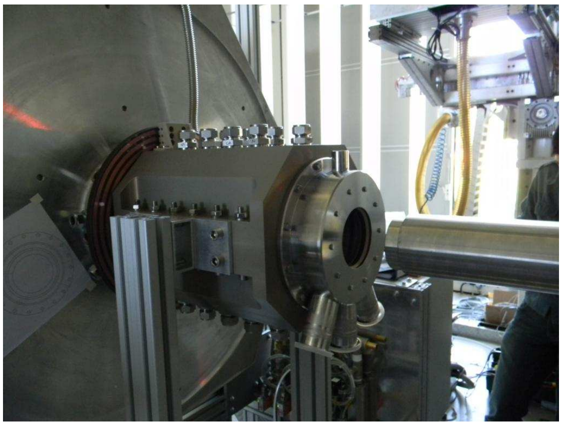


Figure 7a: Rotary joint attached to the rear of the rotary solar reactor.

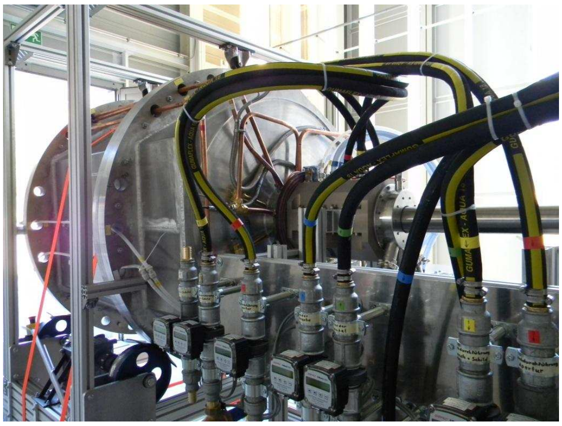


Figure 7b: Cooling water distribution panel and flexible tubes to various water-cooled components.

The functionality of most of the solar reactor components and auxiliary systems has been pre-tested at *PSI*.

Process control system – All processes are controlled by a system based on hardware from National Instruments and Labview software. A user-friendly human machine interface (HMI) allows control of motors, pumps, and valves; display of temperatures, pressures, and mass flows; setting of alarms and emergency signals; etc.

Electric control system – Two electric control cabinets are being used. One is dedicated to the control of motors for the reactor rotation, the feeder stirring device, the feeder screw, and the feeder linear movement; pumps and valves; etc. The other one is for temperature, pressure and mass flow control; alarms and emergency signals; data acquisition; gas analysis; etc.

Solar pilot plant installation and commissioning

End of May 2011, the pre-assembled 100 kW solar pilot reactor was shipped to Odeillo, France (Fig. 8), where it was fully assembled within less than one week.

Mobile carriage – The reactor and all sub-components, apart from the filters and the gas analysis equipment, are installed on a mobile Bosch profile system (Bosch Rexroth AG), as shown in Fig. 4. The Bosch profile is mounted on a mobile carriage system (2.8 m x 3.2 m) to allow manageable and flexible transport from the ground floor to the solar tower focal point as well as to facilitate on-site maintenance tasks (Fig. 9).

Figure 8: Solar reactor being moved into the MWSF tower.

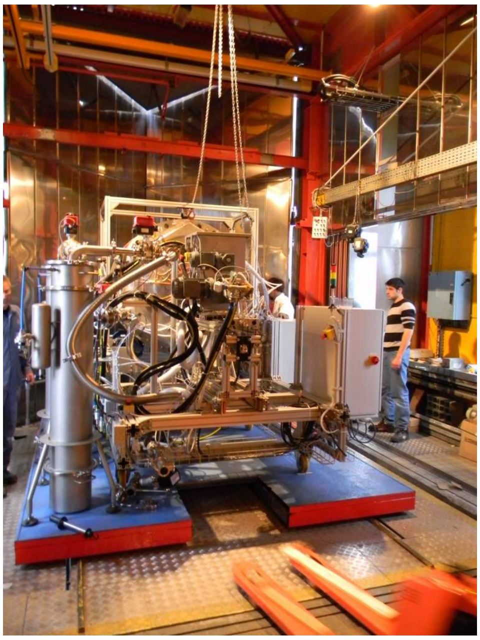


Figure 9: Solar pilot plant mounted on mobile carriage (left) in solar tower experimental platform of MWSF, Odeillo, France (right). Remark that the radiation shield has not been mounted yet.

Radiation shield – A large water-cooled radiation shield protects the experimental setup from the concentrated solar radiation (Fig. 10). It consists of two side panels provided by *PROMES-CNRS* and a special center panel – adapted to the dimensions of the 100 kW solar reactor – provided by *PSI*. The power can be controlled by two shutter doors in front of the experimental platform.

Commissioning – Installation on the experimental platform in the solar tower and commissioning of the complete plant required ten days. Functionality tests of all system components included cooling water, gas supply and off-gas piping, electrical and electronic connections, process control and data acquisition systems.

Safety control – The operators sitting in the control room behind the experimental platform have full control of the heliostat field and the solar experiment, which is continuously monitored by cameras. Safety is warranted by implementing emergency control equipment.

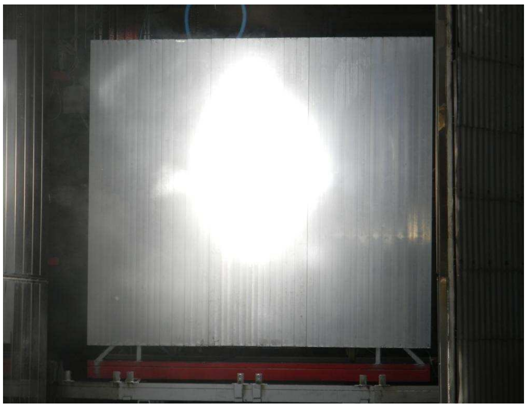


Figure 10: Water-cooled radiation shield protecting the experimental setup from the concentrated solar radiation.

Experimental procedure

In order to prepare a solar experiment, the solar pilot plant mounted on the mobile Bosch profile is retracted to make possible the access to the reactor cavity and ease mounting the window and the reactor front shield. Prior to starting an experimental run, the complete mobile carriage is being moved forward until the reactor aperture intercepts the focal plane. Cooling water supply to all cooled parts is enabled, while the protective Ar flows through the radial and tangential nozzles are both set to 15 l_N/min.

For a typical experimental run, six center heliostats out of 63 in total (each with a mirror area of 45 m^2) are set into track mode (Fig. 11). Subsequently, the shutter doors are opened in small steps to allow steady heat-up and to alleviate thermal stress on the cavity lining. To further increase the radiative power delivered to the solar reactor, more heliostats are set into tracking position (up to 25 heliostats in total, depending on the goal of the experimental run).

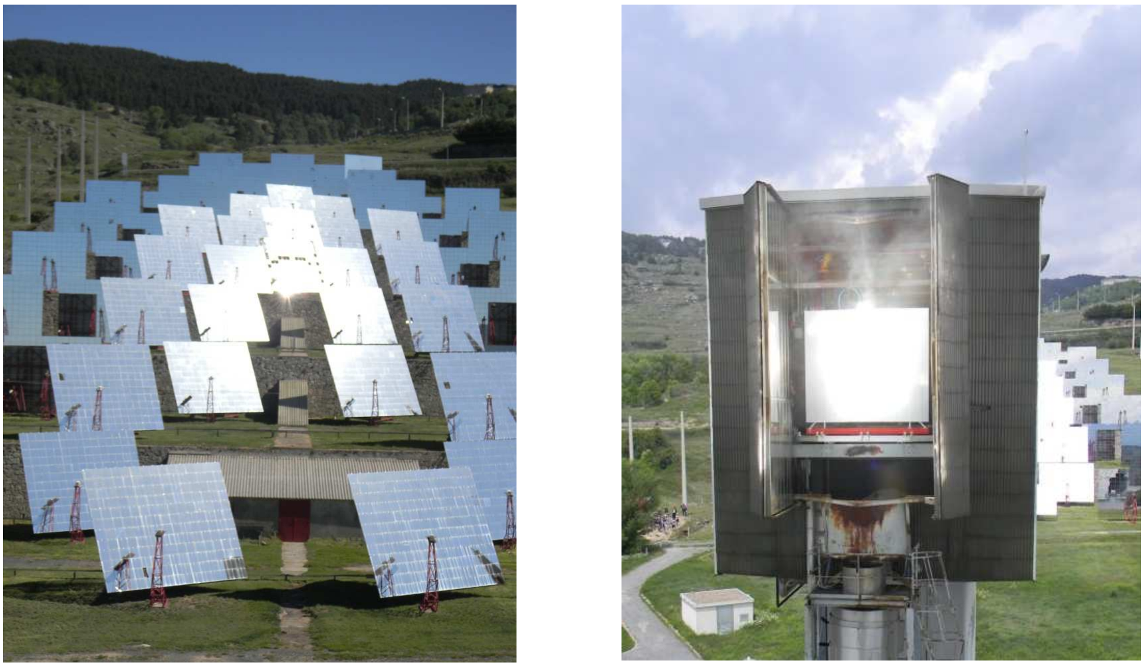


Figure 11: Heliostat field with central heliostats tracking the sun (left); doors of the MWSF tower partly open showing spilled radiation on the radiation shield (right).

Once the reference temperature T1 (see Fig. 2) approaches 1773 K, the filters are swapped and the Ar flow to the quench system is gradually set to 1500 l_N/min. At 1873 K, the feeding routine is started to line the bottom wall of the cavity with a batch of ZnO particles. The reactor is kept at or slightly above this temperature (T1, Fig. 13a) while dissociating ZnO as long as the weather conditions are suitable, Fig. 13c.

During the cooling down of the reactor cavity, both Ar flow rates at the window are initially maintained at 15 l_N/min and then reduced to 10 l_N/min as soon as T1 drops below 1273 K. The gas flow is kept running overnight to prevent re-oxidation of the produced Zn(s), and the cooling water is kept flowing to protect the window and quench unit from over-heating.

Experimental results

Eleven experimental runs with more than 60 hours of on-sun testing were performed in the MWSF. Among them were eight heat-up experiments to cure the refractory materials by evaporating residual water within the insulation (stemming from the manufacturing process) and removing organic binding compounds. For that purpose, the window was detached and the feeder was retracted to facilitate the water vapor exiting the reactor (Fig. 12). The duration of these experiments was between three and seven hours, and the maximum temperatures reached between 803 K and 1796 K (T1, measured behind the alumina tiles). Drying the cavity, however, led to shrinking of the insulation layers and to the formation of gaps between the outer ceramic layer (L4, see Fig. 2) and the reactor shell. Subsequently, the rotational movement of the reactor imposed mechanical stress on the cavity lining and resulted in alumina tiles being detached. Although the damaged cavity was repaired quickly by gluing the tiles onto the insulation, further runs

Figure 12: Residual water vapor exiting the reactor outlet tube placed within the rotary joint. Feeder (left) retracted.

were performed without rotating the reactor. For the last three experimental runs with the goal to dissociate ZnO and produce solar Zn, the window was attached to the reactor front and the feeding and quench systems were made operational. The duration of each of these experiments was between five and six hours, and the maximum operational temperature (T1) was between 1873 K and 1903 K. Due to intermittent solar radiation caused by cloud coverage of the sky, most of the experiments were disturbed or had to be stopped untimely.

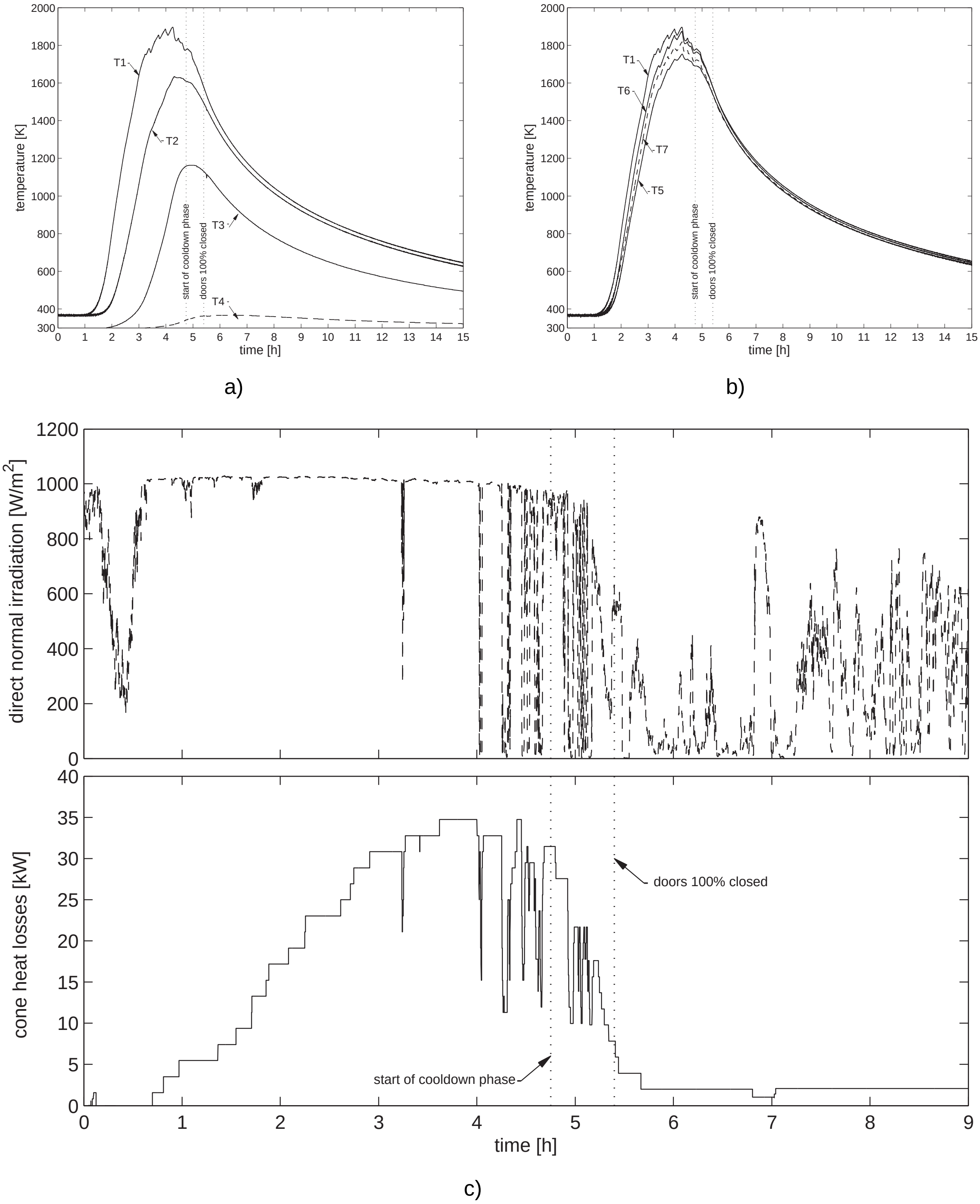


Figure 13: a) Temperature devolution vs. experimental time for thermocouples at position T1, T2, T3 and T4; b) Temperature devolution vs. experimental time for thermocouples at position T1, T5, T6 and T7; c) Direct normal irradiation (DNI, real-time data provided by *PROMES-CNRS*) and heat loss at the front cone calculated from the temperature difference of the cooling water flow vs. the experimental time. From [4].

Figure 13 depicts preliminary results from a typical solar experiment for ZnO dissociation. The temperature devolution with time is shown in Fig. 13a across the cavity insulation for T1 (behind the alumina tiles), T2, T3, and T4 (inside the reactor shell), and in Fig. 13b along the cylindrical cavity lining for T5 (front), T1 (center), T6 (back), and T7 (rear wall). The location of the thermocouples is indicated in Fig. 2. The highest heating rate reached at T1 was 84.5 K/min. Unsteady behavior close to the maximum temperature (between 4 and 5 hours) is due to clouds, which influenced the direct normal irradiation (DNI, see Fig. 13c) and, thus, the power input to the reactor. The highest cooling rate reached was 5.4 K/min after the power input was completely removed (heliostats on stand-by and doors fully closed). Neither the maximum heating rate nor the maximum cooling rate introduced unmanageable temperature tensions for the ceramic insulation and the alumina tiles contained within the reactor shell.

Figure 13c depicts the heat loss at the front cone calculated from the temperature difference of the cooling water flow vs. the experimental time. Up to 35 kW have to be cooled away at the front cone alone, when the highest power input is reached (doors fully open, 25 heliostats in track mode). At steady state, the heat loss almost instantaneously followed the DNI, which was characterized by intermittent solar radiation due to clouds that eventually impeded continuation of the experiment shortly after starting the ZnO dissociation.

Conclusions

A 100 kW pilot plant for the solar thermal dissociation of ZnO was designed and fabricated at *PSI*. A first experimental campaign of six weeks was scheduled and conducted in June/July 2011 at the 1 MW Solar Furnace (MWSF) in Odeillo, France. More than 60 hours of on-sun testing in the MWSF were recorded, each experiment lasting between three and seven hours. All systems of the solar pilot plant have been tested and qualified. Valuable operational experience was gathered and will help to further improve the current design for the second experimental campaign planned for 2012. It aims at optimizing the reactor performance by implementing a modified quench unit and by operating the reactor at higher temperatures using improved high-temperature wall materials. The goal will be to reach a Zn yield exceeding 50 % and a solar-to-chemical energy conversion efficiency approaching 10 %. The results from this research will extent the ability to store solar energy as a fuel – such as Zn, H_2, or syngas – in a manner that increases the chances of having a sustainable solution to the current world problem of being dependent on a limited supply of fossil fuels.

National Cooperation

The Solar Technology Laboratory at *PSI* is working jointly with the Professorship in Renewable Energy Carriers at *ETH* Zürich.

National cooperation is performed within the framework of

- *Hydropole – Swiss Hydrogen Association* (*PSI* Representative: Dr. Christian Wieckert)
- *Solar Receiver Development for Concentrating Solar Power Systems* (Industrial Project with *ALE AirLight*) – Solar receiver coupled with trough concentrator for a Rankine-based electricity generation system.
- *High-temperature Thermal Storage System for Concentrating Solar Power* (Industrial Project with *ALE AirLight*) – Cost-effective and efficient thermal storage based on a packed bed of rocks with air as working fluid.
- *Inflated Photovoltaic Ultra-light Mirror Concentrators* (Industrial Project with *ALE AirLight*) – Cost-competitive innovative concentrating photovoltaic (CPV) system
- *Solar-driven Combined Cycles* (Industrial Project with *Alstom*) – Novel solar receiver for heating compressed air to the entrance conditions of a gas turbine, as part of a combined cycle for power generation.

– *Solar Fuels for Cement Manufacturing* (Industrial Project with *Holcim*) – High-temperature solar heat for upgrading carbonaceous feedstock to produce high-quality syngas.

Current collaboration with Swiss companies:

Switzerland	*Bühler AG,* Uzwil
	ALE Airlight Energy SA, Biasca
	Alstom Power Service, Baden-Dättwil; *Alstom Power Systems,* Birr
	Holcim, Holderbank
	IBM Zurich Research Laboratory, Rüschlikon

Current collaboration and synergism with other Swiss research laboratories:

Switzerland	*EMPA* Dübendorf – Laboratory for Solid State Chemistry and Catalysis (Prof. A. Weidenkaff)
	ETH Zürich – Particle Technology Laboratory (Prof. S. Pratsinis)

International Cooperation

International cooperation is being performed within the framework of

– *IEA's SolarPACES Implementing Agreement* (Task II – ***Solar Chemistry Research***; Operating Agent: Dr. A. Meier)

– *IEA's Hydrogen Implementing Agreement* (Task 25 – ***High Temperature Hydrogen Production Processes***; Swiss Representative: Dr. A. Meier)

– *Strategic Alliance* between *PSI* and *CIEMAT* (Spain) – **Roadmap to Solar Hydrogen Production**.

– *IPHE – International Partnership for the Hydrogen Economy* (Project: ***Solar driven high temperature thermochemical production of hydrogen***; Swiss Representative: Prof. Dr. A. Steinfeld*).* Participants: *CIEMAT* (Spain), *CNRS* (France), *DLR* (Germany), *U. Colorado* (USA), *ETH* & *PSI* (Switzerland), *NU* & *TIT* (Japan), *WIS* (Israel).

– *SOLLAB – Alliance of European Laboratories on solar thermal concentrating systems*. Collaboration of five leading European solar research laboratories, namely *CIEMAT* (Spain), *CNRS* (France), *DLR* (Germany), *ETH* & *PSI* (Switzerland); Swiss Representative: Prof. Dr. A. Steinfeld.

– *EERA – European Energy Research Alliance*. Joint Program on Concentrated Solar Power (CSP). Participants: *CEA* (France), *CIEMAT* (Spain), *CNRS* (France), *DLR* (Germany), *ENEA* (Italy), *ETHZ* (Switzerland), *FhG-IDE* (Germany), *IMDEA* (Spain), *LNEG* (Portugal), *PSI* (Switzerland), *Uni Perpignan* (France). Swiss Representative: Prof. Dr. A. Wokaun; Swiss Representative for CSP Joint Program: Dr. A. Meier.

– *SFERA – Solar Facilities for the European Research Area* (EU Project). Partners: *CIEMAT* (Spain), *CNRS* (France), *DLR* (Germany), *ENEA* (Italy), *PSI* (Switzerland), WIS (Israel)

– *SynPet* (Industrial Project with *PDVSA*) – Solar steam-gasification of petroleum coke (petcoke).

– *TCSPower* (EU Project) – Thermo-chemical energy storage for concentrated solar power plants.

Current collaboration with international companies:

Germany	*Siemens / Steinmüller Engineering GmbH*, Gummersbach
Venezuela	*PDVSA* – Petróleos e Venezuela S.A., Caracas

Current collaboration and synergism with other international research laboratories:

Australia	*ANU* – Australian National University, Canberra
	CSIRO – Commonwealth Scientific and Industrial Research Organisation, Newcastle, NSW
France	*CNRS* – Centre National de la Recherche Scientifique, Odeillo
Germany	*DLR* – Deutsches Zentrum für Luft- und Raumfahrt, Köln & Stuttgart
Israel	*WIS* – Weizmann Institute of Science, Rehovot
Italy	*ENEA* – Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Roma
Japan	*TIT* – Tokyo Institute of Technology, Tokyo
Spain	*CIEMAT* – Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Madrid & Almería
	IMDEA Energías – Instituto Madrileño de Estudios Avanzados, Móstoles
USA	*Caltech* – California Institute of Technology, Pasadena, USA
	NREL – National Renewable Energy Laboratories, Golden, CO
	SNL – Sandia National Laboratory, Albuquerque, NM, & Livermore, CA
	UC – University of Colorado, Boulder, CO

Evaluation 2011 and Outlook 2012

Achievements 2011

In 2011, the main achievement was the fabrication and initial testing of the 100 kW solar pilot plant for the ZnO dissociation. End of May, the complete solar reactor together with auxiliary equipment was shipped from *PSI* to Odeillo, France, where a total of eleven on-sun experiments were performed during June/July.

1st solar experimental campaign – Valuable initial operational experience with the scale-up reactor has been obtained at the MWSF. Preliminary experimental results have been presented at the SolarPACES Conference in Granada, Spain [4].

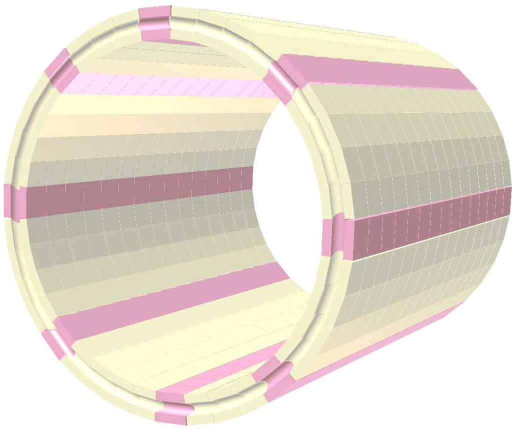


Figure 14: Proposed self-supporting cylindrical cavity lining made of tongue and groove refractory bricks.

Refurbishment of reactor cavity – After the experimental campaign, the whole 100 kW pilot plant was shipped back to *PSI* where it is being refurbished and optimized. Major work is dedicated to improve the cavity lining using a self-supporting structure consisting of high-temperature refractory materials. The evaluation of various concepts is in progress. One promising solution comprises tongue and groove refractory bricks for the cylindrical cavity lining (Fig. 14).

Further modifications – A new ceramic multi-layer coating will be applied to the water-cooled front cone. Various coatings on metallic copper support plates have been supplied by the manufacturer (Sulzer Metco AG) and their feasibility is being tested at *PSI*'s Solar Simulator. In addition, to avoid over-heating of the feeder mantle, the water-cooling of the double-walled feeding tube is being improved and the same coating will be applied as for the front cone.

Outlook 2012

The second phase of the current project („Pilot Phase") has started in January 2010 and will end in February 2013, with a delay of about one year. Due to the complex and time-consuming refurbishment of the reactor cavity and other components, the second experimental campaign at the MWSF in Odeillo, France, has to be postponed to June/July 2012. The goal will be to demonstrate reliable reactor operation and to optimize the reactor performance in order to reach a solar-to-chemical energy conversion efficiency approaching 10%.

Pilot plant refurbishment and optimization – The detailed planning for the refurbishment and optimization of the 100 kW solar pilot plant is in progress (WP3). Fabrication and purchase of new components – cavity lining, front cone coating, and feeding system – will be completed in March 2012. Both the process control and the data acquisition systems are being modified and will be tested at *PSI* prior to shipping the 100 kW pilot plant to Odeillo.

2nd solar experimental campaign – The solar reactor and its peripherals will be experimentally tested at the MWSF in Odeillo, France (WP4).

Heat transfer model validation and economic analysis – The experimental data will be used to validate the numerical reactor models (WP6). Finally, the findings of the pilot tests will lead to the conceptual design and economic analysis of an industrial solar plant (WP5).

Goals for 2012

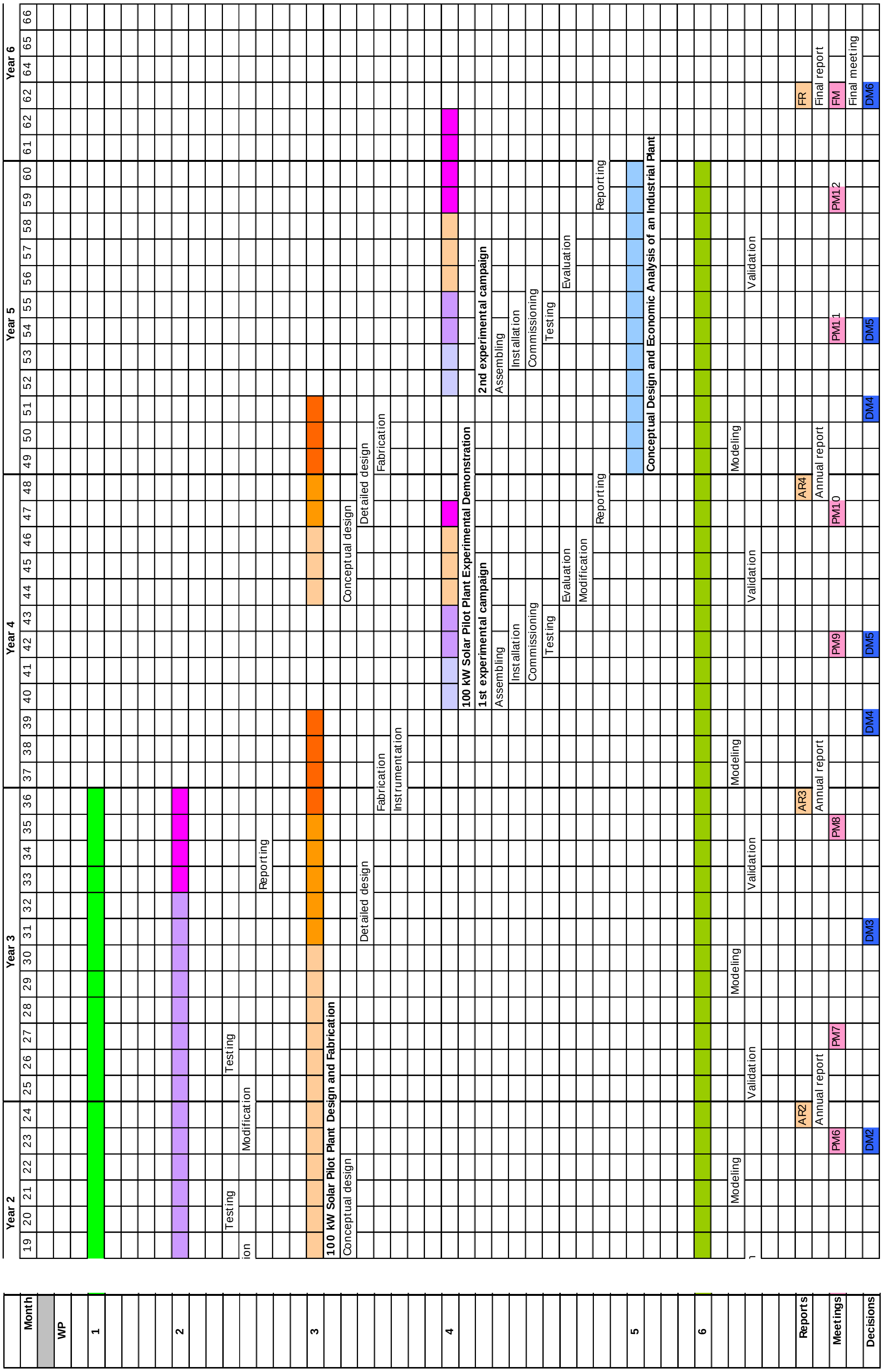
- Until end of March 2012, the 100 kW solar pilot reactor will be modified and optimized at *PSI.* In particular, the reactor cavity will be completely renewed.
- In April and May 2012, the solar reactor and the most critical components will be assembled and pre-tested at *PSI*. End of May 2012, the pilot plant will be shipped to Odeillo, France.
- The second experimental campaign at the MWSF in Odeillo, France, is scheduled for June/July 2012. The main goal is reliable reactor operation without mechanical problems:
    - Aerodynamic window protection from condensing gases
    - Thermal shock resistant and chemically stable high-temperature materials
    - Efficient feeding of ZnO powder and removal of solid products
- For each experimental run, perform
    - Online measurement of O_2 in product stream to prove the successful dissociation of ZnO (Goal for 2nd campaign: ZnO dissociation rate >8 kg/h)
    - Chemical analysis to determine the Zn content in the products (Goal for 2nd campaign: Zn yield >50%)
    - Continuous temperature measurement at various positions in the reactor to validate the transient heat transfer model
    - Mass and energy balance to get information on the process development and the heat losses in the solar reactor
    - Solar-to-chemical energy conversion efficiency calculation (Goal for 2nd campaign: η > 10%)
- Conceptual design and economic analysis of industrial solar zinc production plant
    - Layout and cost estimate of first-of-its-kind industrial demonstration plant for the production of zinc (e.g. 10-50 MW_{th})

Project timeline for 2012

The project is delayed by about one year. The modified timeline for 2012 is presented in the table below. For details of the work packages involved (WP3, WP5, WP4, and WP6), see project proposal [1].

Task	Input from	Activity	Begin	End	Deliverables, Milestones & Remarks
3.3	3.1 3.2 6.2 6.3	Update detailed design of reactor and periphery (including process control)	01.09.11	29.02.12	D3.1 (month 48): Final set of technical drawings. D3.2 (month 50): Process control scheme updated.
3.4	3.3	Fabricate modified components of reactor and periphery (cavity, feeder, front cone)	01.01.12	31.03.12	M3.4 (month 51): 100 kW pilot reactor ready.
3.5		Measurement and control instrumentation	01.11.11	31.03.12	M3.2 (month 51): Process control system operational.
4.1	3.4	Installation	29.05.12	01.06.12	M4.1 (month 53): Solar tower facility available for second campaign. M4.2 (month 53): Measurement and control instrumentation ready.
4.2	4.1	Commissioning	01.06.12	15.06.12	M4.3. (month 54): Reliable reactor operation proved. M4.4 (month 54): Complete pilot plant commissioned.
4.3	4.2	Parametric testing and data processing	15.06.12	31.07.12	
4.4	4.3	Performance evaluation	15.06.12	31.10.12	D4.1 (month 58): Performance map of 100 kW solar pilot plant, incl. thermal reactor efficiency.
5.1	3.3 6.4 6.5 6.6	Large-scale conceptual design	01.01.12	31.12.12	M5.1 (month 60): Conceptual design of industrial (e.g. 10-50 MW) solar demonstration plant.
5.2	5.1	System economic analysis	01.01.12	31.12.12	
6.3	6.2	Heat transfer and fluid flow model	01.10.09	31.12.12	
6.4	4.4 6.3	Model validation	01.08.12	31.12.12	D6.1 (month 60): Validated reactor model to serve as a tool for design, optimization, and scale-up.
6.5	6.4	Optimization of reactor	01.09.12	31.12.12	
6.6	6.2 6.5	Up-scaling reactor to large-scale industrial demonstration	01.09.12	31.12.12	

Timetable (updated)



Publications

The following is a list of recent publications originating from or related to the *Solar Zinc Project* [1], [2].

Book Chapter

– A. Meier: ***Solar Fuel Production***, Contributing Author to Chapter 3 "Direct Solar Energy" in: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. v. Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2011.

Peer-reviewed Journals

– I. Alxneit: ***Measuring temperatures in a high concentration solar simulator – Demonstration of the principle***, Solar Energy **85**, 516-522, 2011.

– R. Bader, A. Pedretti, A. Steinfeld: ***A 9m-aperture solar parabolic trough concentrator based on a multilayer polymer membrane mounted on a concrete structure***, ASME J. Sol. Energy Eng. **133**, 031016 1-12, 2011.

– P. Coray, W. Lipinski, A. Steinfeld: ***Spectroscopic goniometry system for determining thermal radiative properties of participating media***, Exp. Heat Transfer **24**, 300-312, 2011.

– Cooper T., Steinfeld A.: ***Derivation of the angular dispersion error distribution of mirror surfaces for Monte Carlo ray-tracing applications***, ASME Journal of Solar Energy Engineering **133**, 44501 1-4, 2011.

– M. Hänchen, S. Brückner, A. Steinfeld: ***High-temperature thermal storage using a packed bed of rocks – Heat transfer analysis and experimental validation***, Appl. Therm. Eng. **31**, 1798-1806, 2011.

– M. Halmann, A. Frei, A. Steinfeld: ***Vacuum carbothermic reduction of Al_2O_3, BeO, MgO-CaO, TiO_2, ZrO_2, HfO_2+ZrO_2, SiO_2, SiO_2+Fe_2O_3, and GeO_2 to the metals. A thermodynamic study***, Miner. Process. Extr. Metall. Rev. **32**, 247-266, 2011.

– S. Haussener, I. Jerjen, P. Wyss, A. Steinfeld: ***Tomography-based determination of effective transport properties for reacting porous media***, ASME J. Heat Transfer **134**, 012601 1, 2011.

– I. Hischier, P. Pozivil, A. Steinfeld: ***A modular ceramic cavity-receiver for high-temperature high-concentration solar applications***, ASME J. Sol. Energy Eng. **134**, 011004 1-6, 2011.

– P. Kreider, H. Funke, K. Kuche, M. Schmidt, A. Steinfeld, A.W. Weimer: ***Manganese oxide based thermochemical hydrogen production cycle***, Int. J. Hydrogen Energy **36**, 7028-7037, 2011.

– M. Krüsi, M.E. Galvez, M. Halmann, A. Steinfeld: ***Solar aluminum production by vacuum carbothermal reduction of alumina – Thermodynamic and experimental analyses***, Metall. Mater. Trans. B **42B**, 254-260, 2011.

– P.G. Loutzenhiser, A. Stamatiou, W. Villasmil, A. Meier, A. Steinfeld: ***Concentrated solar energy for thermochemically producing liquid fuels from CO_2 and H_2O***, J. Metals **63**, 32-34, 2011.

– P.G. Loutzenhiser, F. Barthel, A. Stamatiou, A. Steinfeld: ***CO_2 reduction with Zn particles in a packed-bed reactor***, AIChE J. **57**, 2529-2534, 2011.

- P.G. Loutzenhiser, A. Steinfeld: ***Solar syngas production from CO_2 and H_2O in a two-step thermochemical cycle via Zn/ZnO redox reactions: Thermodynamic cycle analysis***, Int. J. Hydrogen Energy **36**, 12141-12147, 2011.
- G. Maag, C. Falter, A. Steinfeld: ***Temperature of a quartz/sapphire window in a solar cavity-receiver***, ASME J. Sol. Energy Eng. **133**, 014501 1-4, 2011.
- N. Piatkowski, C. Wieckert, A.W. Weimer, A. Steinfeld: ***Solar-driven gasification of carbonaceous feedstock – A review***, Energy Environ. Sci. **4**, 73-82, 2011.
- R. Pitz-Paal, N. Botero, A. Steinfeld: ***Heliostat field layout optimization for high-temperature solar thermochemical processing***, Solar Energy **85**, 334-343, 2011.
- M. Roesle, V. Coskun, A. Steinfeld: ***Numerical analysis of heat loss from a parabolic trough absorber tube with active vacuum system***, ASME J. Sol. Energy Eng. **133**, 031015 1-5, 2011.
- C. Suter, P. Tomes, A. Weidenkaff, A. Steinfeld: ***A solar cavity-receiver packed with an array of thermoelectric converter modules***, Solar Energy **85**, 1511-1518, 2011.
- P. Tomes, C. Suter, M. Trottmann, A. Steinfeld, A. Weidenkaff: ***Thermoelectric oxide modules (TOMs) tested in a solar cavity-receiver***, J. Mater. Res. **26**, 1975-1982, 2011.
- J. Wurzbacher, C. Gebald, A. Steinfeld: ***Separation of CO_2 from air by temperature-vacuum swing adsorption using diamine-functionalized silica gel***, Energy Environ. Sci. **4**, 3584-3592, 2011.
- H. Yoon, T. Cooper, A. Steinfeld: ***Non-catalytic autothermal gasification of woody biomass***, Int. J. Hydrogen Energy **36**, 7852-7860, 2011.
- E. Zermatten, S. Haussener, M. Schneebeli, A. Steinfeld: ***Tomography-based determination of permeability and Dupuit-Forchheimer coefficient of characteristic snow samples***, J. Glaciology **57**, 811-816, 2011.

Bachelor Theses

- M. Leoni: ***Determination of thermo-physical properties of CO_2 capture sorbent***, PSI Villigen and ETH Zürich, July 2011.
- F. Müller: ***Thermally-driven metal oxide cycles for inert gas recycling***, PSI Villigen and ETH Zürich, July 2011.
- D.-A. Tian: ***Vacuum distillation of silicon via carbothermal reduction of SiO_2 with concentrated solar energy***, PSI Villigen and ETH Zürich, July 2011.
- M. Weirich: ***Syngas production via a solar thermochemical cycle based on FeO/Fe_3O_4 redox reactions – Thermogravimeter analysis of the 2nd step***, PSI Villigen and ETH Zürich, March 2011.

Semester Theses

- G. Putzi: ***Analysis of chemical kinetics of the Mn_3O_4/MnO reduction reaction in high temperature / high-solar-radiation flux conditions***, PSI Villigen and ETH Zürich, December 2011.
- D. Weibel: ***Experimental investigation of a volumetric air receiver for concentrated solar power***, PSI Villigen and ETH Zürich, December 2011.
- M. Welte: ***Dopant effects on the reduction of cerium oxide for two-step thermochemical cycles for solar fuel production***, PSI Villigen and ETH Zürich, June 2011.

Conference Proceedings / Other Papers

- I. Alxneit, G. Dibowski: ***Spectral characterization of solar simulators***, Proc. 17th SolarPACES Conference, Granada, Spain, September 20-23, 2011.
- C. Hutter, W. Villasmil, M. Chambon, A. Meier: ***Operational experience with a 100 kW solar pilot plant for thermal dissociation of zinc oxide***, Proc. 17th SolarPACES Conference, Granada, Spain, September 20-23, 2011.
- P.G. Loutzenhiser, A. Stamatiou, W. Villasmil, A. Steinfeld: ***Concentrated solar energy for thermochemically producing liquid fuels from CO_2 and H_2O***, TMS Symposium Carbon Dioxide and Other Greenhouse Gas Reduction Metallurgy, San Diego, USA, February 27 - March 3, 2011.
- P.G. Loutzenhiser, A. Steinfeld: ***Solar syngas production from CO_2 and H_2O in a two-step thermochemical cycle via Zn/ZnO redox reactions: Thermodynamic cycle analysis***, Proc. International Conference on Hydrogen Production, Thessaloniki, Greece, June 19-22, 2011.
- A. Meier: ***Task II: Solar Chemistry Research***, International Energy Agency – SolarPACES Annual Report 2010, C. Richter ed., Chapter 4, 2011.
- M. Pravettoni, M. Cadruvi, T. Cooper, S. Dittmann, G. Ambrosetti, A. Steinfeld: ***INPHOCUS - a novel design for concentration photovoltaics: characterization of the receiver and light uniformity analysis***, Proc. 26th EU PVSEC European Photovoltaic Solar Energy Conference, Hamburg, Germany, September 5-8, 2011.
- M. Roesle, V. Coskun, A. Steinfeld: ***Numerical analysis of heat loss from a parabolic trough absorber tube with active vacuum system***, ASME 5th International Conference on Energy Sustainability & 9th Fuel Cell Science, Washington D.C., USA, August 7-10, 2011.
- E. Rojas, R. Bayón, R. Adinberg, F. Fabrizi, C. Hutter, D. Laing, X. Py: ***Towards standardization of testing storage prototypes***, Proc. 17th SolarPACES Conference, Granada, Spain, September 20-23, 2011.
- C. Suter, Z. Jovanovic, A. Steinfeld: ***A 1 kW_{el} thermoelectric stack for geothermal power generation — Modeling and geometrical optimization***, Proc. 9th European Conference on Thermoelectrics, Thessaloniki, Greece, September 28-30, 2011.
- C. Wieckert, N. Piatkowski, A. Steinfeld, A. Obrist, P. von Zedtwitz: ***Solar reactor prototype testing for solar steam-gasification of carbonaceous feedstocks to syngas***, Proc. World Engineers Convention, Geneva, September 4-9, 2011.
- G. Zanganeh, A. Pedretti, A. Steinfeld: ***A packed bed of rocks for high-temperature thermal storage of concentrating solar energy***, Proc. World Engineers Convention, Geneva, September 4-9, 2011.

Invited Talks

- I. Alxneit: ***Temperature measurement in solar furnaces and solar simulators***, 2nd SFERA Winter School (Solar Fuels & Materials), ETH Zürich, March 24-25, 2011.
- M. Chambon: ***Solar thermochemical cycles based on the ZnO/Zn or SnO_2/SnO redox couples***, 2nd SFERA Winter School (Solar Fuels & Materials), ETH Zürich, March 24-25, 2011.
- C. Hutter: ***Treibstoffe aus konzentrierter Sonnenenergie***,
  1) Runder Tisch in Zürich – Vortrag und Diskussion, ASPO Schweiz, April 27, 2011.
  2) Volkshochschule Bad Zurzach, December 1, 2011.
- C. Hutter: ***Benzin aus Wasser, CO_2 und Sonnenlicht***, F. Hoffmann-La Roche AG Engineering Platform, December 1, 2011.

- A. Meier: ***The Zn-based thermochemical cycle for splitting H_2O and CO_2***, 2nd SFERA Winter School (Solar Fuels & Materials), ETH Zürich, March 24-25, 2011.
- A. Meier: ***Trends in solar chemistry***, 17th SolarPACES Conference, Granada, Spain, September 23, 2011.
- A. Steinfeld: ***Liquid fuels from water, CO_2, and solar energy***,
  1) IMDEA Energy, Madrid, Spain, April 4, 2011.
  2) The University of New South Wales, Sydney, Australia, July 20, 2011.
- A. Steinfeld: ***Concentrated solar energy for high-temperature applications***, Keynote, Arica, Chile, June 24, 2011.
- A. Steinfeld: ***Fuels from sunlight, water, and CO_2 via thermochemical processes***, Keynote, APCSEET 2011 - 8th Asia Pacific Conference on Sustainable Energy & Environmental Technologies, Adelaide, Australia, July 12, 2011.
- A. Steinfeld: ***Solar thermochemical processes for the extractive metallurgical industry***, Swinburne University of Technology, Melbourne, Australia, July 18, 2011.
- A. Steinfeld: ***Flüssige Treibstoffe aus Wasser, CO_2, und Sonnenlicht***, Schweizer Technion-Gesellschaft, Zürich, October 26, 2011.
- C. Wieckert: ***Konzentrierte Sonnenenergie – Optionen für die zukünftige Energieversorgung***, Rotary Club Baden, January 11, 2011.
- C. Wieckert: ***Solar carbothermic production of zinc***, 2nd SFERA Winter School (Solar Fuels & Materials), ETH Zürich, March 24-25, 2011.

Contributions to Media

- A. Meier, C. Hutter: ***Schweizer Forscher speichern Sonnenenergie in Zink***, Fernsehbericht: „Einstein“ im Schweizer Fernsehen SF1, October 6, 2011.

Other Talks

- I. Alxneit, G. Dibowski: ***Spectral characterization of solar simulators***, Proc. 17th SolarPACES Conference, Granada, Spain, September 20-23, 2011.
- C. Hutter, W. Villasmil, M. Chambon, A. Meier: ***Operational experience with a 100 kW solar pilot plant for thermal dissociation of zinc oxide***, Proc. 17th SolarPACES Conference, Granada, Spain, September 20-23, 2011.
- P. Loutzenhiser, A. Stamatiou, D. Gstoehl, A. Meier, A. Steinfeld: ***Concentrated solar power for producing liquid fuels from CO_2 and H_2O***, Proc. TMS Annual Meeting & Exhibition, San Diego, USA, February 27 - March 3, 2011.

References

[1] A. Meier, A. Steinfeld: ***Solar Production of Zinc and Hydrogen – Reactor Optimization for Scale-Up***, BFE-Projekt Nr. 102420/153045, Project Proposal, 2008-2011.

[2] A. Meier, D. Gstöhl: ***Towards Industrial Solar Production of Zinc and Hydrogen – 100 kW Solar Pilot Reactor for ZnO Dissociation***, BFE-Projekt Nr. 103264/154298, Project Proposal, 2010-2011.

[3] A. Meier: ***Solar Production of Zinc and Hydrogen – 100 kW Solar Pilot Reactor for ZnO Dissociation***, BFE Project Proposal, 2012-2013, submitted October 2011.

[4] C. Hutter, W. Villasmil, M. Chambon, A. Meier: ***Operational Experience with a 100 kW Solar Pilot Plant for Thermal Dissociation of Zinc Oxide***, Proc. 17^{th} SolarPACES Conference, Granada, Spain, September 20-23, 2011.

[5] R. Müller, P. Häberling, R.D. Palumbo: ***Further Advances Toward the Development of a Direct Heating Solar Thermal Chemical Reactor for the Thermal Dissociation of ZnO(s)***, *Solar Energy* 80 (5), pp. 500-511, 2006.

[6] R. Müller, W. Lipinski, A. Steinfeld: ***Transient heat transfer in a directly-irradiated solar chemical reactor for the thermal dissociation of ZnO***, *Appl. Thermal Eng.* 28 (5-6), pp. 524-531, 2008.

[7] L.O. Schunk, P. Haeberling, S. Wepf, D. Wuillemin, A. Meier, A. Steinfeld: ***A Receiver-Reactor for the Solar Thermal Dissociation of Zinc Oxide***, *J. Solar Energy Eng*. 130 (2), 021009, 2008.

[8] M.A. Clevinger, K.M. Hill and C.L. Cedeno: ***Phase Equilibria Diagrams: Phase Diagrams for Ceramists: 1995 Cumulative Indexes: Volumes 1-11, Annuals '91-'93, High Tc Monograph***, The American Ceramic Society, Westerville, OH, 1995.

[9] D. Gstöhl, A. Brambilla, L. Schunk, A. Steinfeld: ***A Quenching Apparatus for the Gaseous Products of the Solar Thermal Dissociation of ZnO***, *J. Mater. Sci.* 43, pp. 4729-4736, 2008.