4 Task II: Solar Chemistry Research

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4.1 Nature of Work & Objectives

The primary objective of Task II—Solar Chemistry R&D—is to develop and optimize solar-driven thermo-chemical processes for the production of fuels and materials, and to demonstrate—at industrial scale—their technical and economic feasibility. The revised Task II structure for the current Term (2012-2017) is based on dedicated Activities to reflect the future challenges and to foster active participation of SolarPACES member countries:

- **Activity 1: Solar Fuels (SF)**
  - Demonstrate—at pilot scale—the most advanced processes for the solar production of synthetic gaseous and liquid fuels (e.g., cracking or steam reforming of NG, gasification of carbonaceous materials, carbo-thermal reduction of metal oxides).
  - Demonstrate medium and high temperature steam electrolysis (MTSE & HTSE) and multi-step thermo-chemical processes for the production of hydrogen (e.g., sulfur cycles).
  - Scale up the solar reactor technology of promising two-step H₂O/CO₂-splitting processes for hydrogen and syngas production (e.g., Zn/ZnO & ferrite cycles).

- **Activity 2: Solar Materials (SM)**
  - Process chemical commodities using concentrated sunlight (e.g., aluminum; EU project ENEXAL).

- **Activity 3: Thermo-chemical Storage (TS)**
  - Develop novel thermo-chemical storage systems (e.g., EU project TCSPower).

- **Activity 4: Technology Innovation (TI)**
  - Engineer innovative and cost-efficient high-temperature solar reactor materials and components.
  - Design advanced heat recovery systems.
  - Implement advanced concentrating optics for high solar flux intensities and high temperatures.

- **Activity 5: Research Infrastructure (RI)**
  - Optimize dedicated solar research infrastructure for the thermo-chemical production of fuels (e.g., EU project SFERA).

- **Activity 6: Market Penetration (MP)**
  - Enhance the industry involvement in solar fuels production and promote the market penetration of the most mature solar fuels technologies.
  - Interact with industry, government, and academia to promote the Task II special activity “Roadmap to Solar Fuels” and develop a country-specific strategy for industry involvement and market penetration.

4.2 Organization and Structure

The Task II Operating Agent (OA), currently PSI, Switzerland, is responsible for organization, operation, and reporting. International solar chemical research, development and demonstration efforts are coordinated in cost, task and/or information-sharing activities by National Coordinators (NC), making use of an efficient network, for the rapid exchange of technical and scientific information. In 2015, we welcomed a new NC: Alberto Giaconia from ENEA for Italy. We gratefully acknowledge the service provided by the former NCs: Pietro Tarquini, Italy, and Michael Epstein, Israel (retired, no successor nominated yet). The Task II Annual Meeting provides a forum for presenting and discussing major technological achievements.

The Task II Program of Work offers an up-to-date description of the national and international projects. When appropriate, Task II conducts a status review on novel technologies for assessing their technical and economic feasibility. Task II is continuously striving to
stimulate public awareness of the potential contribution of solar chemistry to clean, sustainable energy services.

### 4.3 Status of Technology

This chapter provides a comprehensive overview of the many ways in which solar chemical technologies may be used for the delivery of clean, sustainable energy services. In 2014, special focus was on the solar thermal production of fuels (hydrogen and syngas) and chemicals for the power, transportation and chemical sectors of the world energy economy.

In 2014, solar chemistry research was presented at two major international conferences:

- **20th SolarPACES Conference**, Beijing, China, September 16-19, 2014; 12 oral presentations and 6 posters were submitted on solar fuels and chemical commodities.

The 28th Task II Annual Meeting was held in conjunction with the 20th SolarPACES Conference, Beijing, China, on September 15, 2014, attracting 19 attendees from 11 countries.

In the following, the most important achievements in 2014 of Task II related projects are summarized with updated information about project participation, objectives, status, and most relevant publications.

#### 4.3.1 ACTIVITY 1: SOLAR FUELS (SF)

**SOLAR-JET – Solar Chemical Reactor Demonstration and Optimization for Long-term Availability of Renewable Jet Fuel**

**Participants:** Bauhaus Luftfahrt e.V. (D), ETH (CH), DLR (D), ARTTIC (F), SHELL GLOBAL SOLUTIONS INT. B.V. (NL)

**Contact:** Aldo Steinfeld, aldo.steinfeld@ethz.ch

**Funding:** EC total contribution: € 2,173,548

**Duration:** June 1, 2011 - May 31, 2015

**Background:** The aim of the SOLAR-JET project is to demonstrate a carbon-neutral path for producing aviation fuel, compatible with current infrastructure, in an economically viable way. The SOLAR-JET project will demonstrate on a laboratory-scale a process that combines concentrated sunlight with CO2 and H2O to produce kerosene by coupling a two-step solar thermochemical cycle based on non-stoichiometric ceria redox reactions with the Fischer-Tropsch process.

**Purpose:** The objective is to develop and optimize the solar reactor technology for producing syngas by splitting H2O and CO2 via ceria-based redox cycles, and to further process the syngas to kerosene. Experimental validation of a reactor model for heat/mass transfer and fluid flow will be used for a scaled-up and optimized design.

**Achievements in 2014:** The European consortium SOLARJET has experimentally demonstrated the first ever production of jet fuel via a thermochemical H2O/CO2-splitting cycle using simulated concentrated solar radiation Error! Reference source not found.. The key component of the production process of sustainable “solar kerosene” is a high-temperature solar reactor containing a reticulated porous ceramic (RPC) foam structure made of pure CeO2 undergoing a 2-step redox cyclic process (Figure 4.1). During the first endothermic reduction step at 1450–1600 °C, the RPC was directly exposed to concentrated thermal radiation with power inputs ranging from 2.8 to 3.8 kW and mean solar flux concentration ratios of up to 3000 suns. In the subsequent exothermic oxidation step at 700–1200 °C, the reduced ceria was stoichiometrically re-oxidized with CO2 and/or H2O to generate CO and/or H2. The RPC featured dual-scale porosity: millimeter-size pores for volumetric radiation absorption during reduction and micrometer-size pores within its struts for enhanced oxidation rates. For cycle duration of 25 min, mean reduction rates were 0.17 mL O2 min–1 g–1 CeO2 and mean oxidation rates were 0.60 mL CO min–1 g–1 CeO2. The solar-to-fuel energy conversion efficiency was 1.72%, without sensible heat recovery [4.1]. A total of 291 stable

![Figure 4.1](image)

(a) Schematic of the experimental setup, featuring the main system components of the production chain to solar kerosene from H2O and CO2 via the ceria-based thermochemical redox cycle. (b) Schematic of the solar reactor configuration. The cavity-receiver contains a reticulated porous ceramic (RPC) structure, made from ceria, with dual-scale porosity in the millimeter- and micrometer-scale Error! Reference source not found..
redox cycles were performed, yielding 700 standard liters of syngas of composition 33.7% H₂, 19.2% CO, 30.5% CO₂, 0.06% O₂, 0.09% CH₄, and 16.5% Ar, which was compressed to 150 bar and further processed via Fischer–Tropsch synthesis to a mixture of naphtha, gasoil, and kerosene.

**Publications:** Error! Reference source not found.-[4.1]

**Zn-Based Thermochemical Cycle for Splitting H₂O and CO₂**

**Participants:** PSI (CH), ETH (CH)

**Contacts:** Anton Meier, anton.meier@psi.ch
Aldo Steinfeld, aldo.steinfeld@ethz.ch

**Funding:** SFOE – Swiss Federal Office of Energy

**Duration:** January 1, 2003 – December 31, 2015

**Background:** The solar two-step Zn/ZnO redox cycle for splitting H₂O and/or CO₂ inherently operates at high temperatures and utilizes the entire solar spectrum, and as such provides a thermodynamically favorable path to efficient solar fuel production [4.3]. The first, endothermic step is the thermolysis of ZnO to Zn and O₂ using concentrated solar radiation as the source of process heat. The second, non-solar, exothermic step is the reaction of Zn with mixtures of H₂O and CO₂ yielding high-quality syngas (mainly H₂ and CO) and ZnO; the latter is recycled to the first solar step, resulting in the net reactions CO₂ = CO + 0.5O₂ and H₂O = H₂ + 0.5O₂, respectively.

**Purpose:** The main objective of the current research is to scale up the optimized solar reactor technology for the thermal dissociation of ZnO from laboratory scale (solar power input of 10 kWth) to pilot scale (solar power input of 100 kWth). Pilot-scale experimental campaigns are being conducted at the 1 MW Solar Furnace (MWSF) of PROMES-CNRS in Odeillo, France.

**Achievements in 2014:** Promising experimental results for the 100-kWth ZnO pilot plant were obtained in 2014 during two prolonged experimental campaigns in PSI’s high flux solar simulator (HFSS) and the 1 MW solar furnace (MWSF) in Odeillo, France (Figure 4.2). In spring, the pilot plant was mounted in the HFSS and in-situ flow-visualization experiments were conducted in order to prevent particle-laden fluid flows near the window from attenuating transparency by blocking incoming radiation [4.4]. This work has shown that: (i) high-temperature, in-situ flow visualization is possible and effective in assessing flow patterns developed inside the reactor; (ii) there exist three characteristic flow patterns inside the reactor that can be dynamically controlled by use of a set of tangential and radially oriented jets; and (iii) a region of stable protective flow, under a wide range of experimental and operational conditions, is capable of repeatedly and fully suppressing detrimental particle depositions on the window.

These results enabled the successful operation of the reactor in autumn when on-sun experiments were conducted in the MWSF in order to demonstrate the pilot plant technology and characterize its performance [4.5]. The reactor was operated for over 97 hours at temperatures as high as 2064 K; over 28 kg of ZnO was dissociated at reaction rates as high as 28 g/min, measured directly by product collection in the filters, and solar power input varied between 11 and 125 kW, as modeled by ray tracing analysis and confirmed with flux measurements performed in the solar furnace. Figure 4.3 plots ZnO dissociation rate vs. thermal efficiency for the experiments conducted. As expected, thermal efficiency increases linearly with dissociation rate. The product of solar input power and ZnO feed rate (between 1 and 3 kg/hr) is also plotted against dissociation rate in Figure 4.3. It is expected that the combination of these two variables will have diminishing impact on dissociation rate as power input exceeds 130 kW and ZnO feed rates approach the pilot plant capacity of 10 kg/hr. With sufficient experimental time, it is anticipated that thermal Figure 4.2. 100 kW solar ZnO pilot plant layout utilized in experiments conducted at PSI and Odeillo in 2014, with critical components and peripherals labeled [4.5].

Figure 4.3. Reactor thermal efficiency vs. ZnO dissociation rate for the entire range of experimental conditions (left y-axis). The product of reactor power input and reactant feed rate is also plotted vs. dissociation rate (right y-axis). Dashed lines indicate projected results [4.5].
efficiencies of above 10% could have been achieved at dissociation rates approaching 100 g/min.

Publications: Error! Reference source not found.

SolarSynGas – Detailed Understanding of Reactions and Processes for Solar Thermochemical H₂O and CO₂ Splitting

Participants: DLR (D), KIT (D), TU Clausthal (D), ETH (CH)
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Funding: EC funded project, cost shared: € 4,400,000
Duration: October 1, 2012 – Sep. 30, 2017

Background: The solar thermal dissociation of H₂O or CO₂, respectively, directly combines low economic value of its reactants with high economic value of its products and therefore comes in for great commercial interest. It represents a technology free of greenhouse gas emissions and fossil fuels consumption. The challenge is to couple solar energy as the driving energy for the reaction. In order to lower the extremely high operating temperatures required for direct dissociation of H₂O and CO₂ and to eliminate the need for high-temperature gas separation, current research concentrates on the so-called thermo-chemical H₂O/CO₂-splitting cycles. Such “multistep” processes to decompose H₂O/CO₂ into H₂/CO and oxygen via two or more chemical reactions require much lower temperatures than those needed for direct thermolysis. The German Helmholtz Association has set up a Virtual Institute on this topic to understand and use fundamental mechanisms of the redox reactions to form a basis for the synthesis of metal oxide redox materials with improved efficiency and lifetime and to understand the influence of key process parameters [4.6].

Purpose: Main objective is the systematic development of the components necessary for solar fuel generation from water and carbon dioxide: investigation of the processes and materials involved and implementation into solar powered reactor technology. Optimized functional ceramics will be developed as redox materials for solar H₂O and CO₂ splitting. Basic understanding of interrelations between atomic structure and transport, microstructure, reactivity and life time of the materials will be developed to design optimized reactor and process concepts for implementation.

Achievements in 2014: In a fundamental thermodynamic analysis, temperature-entropy (T-S) diagrams combined with a pinch point analysis were introduced, providing a vivid and detailed tool to analyze two-step thermochemical water-splitting processes [4.7]-[4.8]. The impacts of different temperature and pressure conditions, different water conversion rates, and materials entropy change were studied (see e.g. Figure 4.4).

One of the most promising materials development routes goes through doped ceria. Doping ceria with zirconia and analyzing the behavior of the material indicates that a certain Zr-content (0.15 ≤ x ≤ 0.225) enhances the reducibility and therefore the splitting performance (Figure 4.5). Increasing the Zr-content to x=0.15 improved the specific CO₂-splitting performance by 50% compared to pure ceria [4.9]. Further increasing the Zr-content to x = 0.38 diminished the specific yields to values of pure ceria. This finding agrees with theoretical studies attributing the improvements to lattice modification caused by the introduction of Zr⁴⁺. Compared to pure ceria, the most efficient composition

Ce₀.₈₅Zr₀.₁₅O₂ enhances the required reaction conditions by a temperature of 60 K or one order of magnitude of the partial pressure of oxygen p(O₂). Long-term cycling of one hundred cycles was performed revealing declining oxidation kinetics.

Total and open porosity, pore size distribution, mean pore diameter, and specific surface area of dual scale reticulated porous ceramic made of ceria were extracted from computer tomography scans [4.10]. The 3D digital geometry was then applied in direct pore level simulations of Fourier’s law within the solid and the fluid phases for the accurate determination of the effective thermal conductivity at each porosity scale and
combined. The morphological properties and effective thermal conductivity determined by this method serve as an input to volume-averaged models for the design and optimization of solar chemical reactors.

Publications: [4.6]-[4.10]

**EWI-SoHTeK – Hydrogen production by high-temperature electrolysis: Design of a solar receiver concept and techno-economic analysis**

**Participant:** DLR (D)

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**Funding:** DLR (D) internal funding

**Duration:** January 1, 2011 - December 31, 2014

**Background:** Solar high-temperature electrolysis (HTE) is a carbon-free technology offering the potential of high efficiency for renewable hydrogen production [4.11]. The efficiency of the HTE increases at rising temperature as the voltage required for water splitting drops. However, the development of HTE cells shows that materials problems strongly increase at high temperatures. Optimal conditions are found between 600 and 700°C, which is ideal for coupling to a solar tower. However, no concept for a solar HTE process has been demonstrated until now. Therefore, in the project SoHTeK, a solar test receiver will be developed and operated in combination with a techno-economic analysis to show the feasibility of solar HTE.

**Purpose:** The main objectives are: (1) Design and construct a solar test receiver to provide superheated steam for HTE; (2) Operate the test receiver in the high flux solar simulator of DLR in Cologne; (3) Model the solar receiver; (4) Develop flow sheets of solar HTE process at industrial scale; (5) Perform techno-economic analysis of the process.

**Achievements in 2014:** The concept of the new SoHTeK receiver (Figure 4.6) is based on previous work [4.12]. Simulations with ANSYS FLUENT revealed that an increase in efficiency is possible by reversing the direction of flow. The experiments in the high flux solar simulator of DLR demonstrated that temperatures of more than 800°C with a mass flow rate of 10 kg/h can be reached at the outlet of the new receiver (Figure 4.7). It could be confirmed that the receiver operates more efficiently at a flow-through from the front (solar input) to the rear (outlet). A further optimization, in comparison with the old version, is the variable change of the flow direction. In the new receiver, steam can flow in both directions, from the front to the rear and from the rear to the front.

Many process variations were investigated by flow-sheeting [4.13]. The thermodynamically most efficient process was further examined in more detail. An economic analysis was performed to determine the total investment cost of the system and to calculate the hydrogen production cost. The cost-effectiveness analysis was performed according to the method of total revenues required (TRR, Total Revenue Requirement). The total capital requirement of the system was also estimated, including all cost necessary for the purchase and installation of the system components. Direct and indirect costs are distinguished. Direct costs include installation, instrumentation and control engineering, electrical equipment and materials, civil and architectural works. Indirect costs include engineering, supervision and insurance. The before-mentioned shares were taken into account by percentages of equipment purchase costs (PEC).

Publications: [4.11]-[4.13]

**HyCats – New Catalysts and Technologies for Solar Chemical Hydrogen Generation**

**Participants:** H.C. Starck GmbH (D), LUH (D), LIKAT (D), DLR (D), University Bonn (D), ODB-Tec GmbH & Co. KG (D), Zinsser Analytic GmbH (D)
4.6 ANNUAL REPORT 2014 SOLARPACES

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Funding: German Federal Ministry of Education and Research, cost shared: € 3,960,000

Duration: November 1, 2010 - October 30, 2013

Background: Carbon-free production of hydrogen can be achieved by photocatalytic water splitting if solar radiation serves as the source of photons. However, efficiency and durability of catalysts have to be improved in respect of material costs and availability. The project consortium covers the whole range from fundamental research to industrial application. The duration of the project was extended due to a reorganization of the work plan. Final activities took place in 2014.

Purpose: The main purpose of this project is a systematic development of photocatalysts and reactors for hydrogen production via photocatalytic water splitting using concentrated solar light. The scheduled contributions of DLR comprise the development of a suspension reactor and a test facility allowing experiments under concentrated solar irradiation as well as a techno-economic analysis.

Achievements in 2014: The SoCRatus facility (Solar Concentrator with a Rectangular Flat Focus, see Figure 4.8) – a modified linear Fresnel collector – as well as a suspension reactor both developed and constructed at DLR in the scope of the project were extensively tested and successfully employed in solar experiments in the field of photocatalytic water splitting for hydrogen generation [4.14]. The solar concentrator features a geometric concentration ratio of 20.2 along with 87% solar weighted hemispheric reflectance (>80% in UV-A and UV-B) of the 22 aluminum facets. A remarkable homogeneity of the irradiation profile in the focal plane (2500 mm x 100 mm) could be established with a local standard deviation of about 2.4%. The accuracy of the two-axis-tracking system is better than 0.1°. Two of four available identical fluid cycles with controlled temperature were connected to the aforementioned suspension reactor. The reactor provides two parallel reaction chambers which allow the evaluation of two catalytic systems under equal irradiation conditions. Experiments using suspensions of SnNb$_2$O$_6$ with Pt as cocatalyst (provided by H.C. Starck) in water with methanol as sacrificial reagent were carried out in the temperature range between 20°C and 60°C. Simultaneously, a fixed-bed photochemical cell (produced by ODB-Tec) was operated. Generation of hydrogen was detected in both reactor types.

Publication: [4.14]

INNPACTO-SolH2 – Innovative Technologies for Hydrogen Production

Participants: ABENGOA Hydrogen (E), IMDEA Energía (E), CIEMAT (E), Universidad de Sevilla (E)

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Funding: Spanish Ministry of Science and Education (MICINN): € 2,000,000

Duration: June 1, 2011 - June 31, 2014

Background: Many high temperature endothermic reactions for converting solar energy to chemical fuels have been investigated around the world. Improved receiver/reactors have been identified, developed, and assessed for efficiently running thermochemical processes for the production of H$_2$. Within the INNPACTO-SolH2 project, an innovative cavity receiver consisting of multiple tubular reactors for driving ferrites cycles will be investigated.

Purpose: The INNPACTO-SolH2 project aims to develop clean technologies for solar H$_2$ production based on (1) water splitting by mixed-ferrite thermochemical cycles and (2) bioethanol steam reforming. For each of these H$_2$ production routes, independent solar reactor prototypes will be designed, constructed, commissioned and tested on a solar tower at operational temperatures between 1100-1300°C.
Achievements in 2014: The multi-disciplinary research group within this project moved forward during this year in different activities of the project, such as construction and commissioning of the solar plant. The SolH2 facility consisting of a 200 kW_{th} solar receiver is located at 28 m height in the CRS plant (Figure 4.9).

The plant also includes the equipment necessary for the water splitting process, i.e. auxiliary services, N₂ inert gas supply, water, steam generator, compressed air and electricity supply and communications wiring. An additional task comprises the implementation of the control system by adding some new functionality to the heliostat control program.

ALCCONES – Clean Hydrogen Production and Carbon Dioxide Free Alternatives

Participants: IMDEA Energía (E), Universidad J. Carlos I (E), ICP-CSIC (E), CIEMAT (E), SENER (E), ABENGOA Hydrogen (E), Empresarios Agrupados (E)

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Funding: Community of Madrid: € 2,017,000
Duration: October 1, 2014 – October 31, 2017

Background: The ALCCONES project is a very ambitious initiative that involves the R&D public institutions IMDEA Energía (Coordinator), University J. Carlos I, ICP-CSIC and CIEMAT. SENER (a Spanish petroleum company) and ABENGOA Hydrogen (company subsidiary of the ABENGOA group) act as industrial companies with active collaboration and interest in the possible exploitation of the project results. The Spanish acronym AlCConES stands for “Storage and Conversion of Concentrated Solar Power”.

Purpose: The main goal of the program is to develop technologies for the conversion and storage at CSP systems for the efficient production of electricity, industrial process heat and hydrogen. The three objectives that provide functional structure to the work program of ALCCONES are: (1) Flowsheeting and multiobjective system analysis of CSP systems with integration of new thermal fluids; (2) develop new solar receivers and reactors for the efficient operation at high temperatures and with high penetration of photons for high incident flux; (3) develop new storage and dispatching thermal energy systems such as: (a) thermocline beds, (b) encapsulated new PCM (Phase Change Materials), (c) thermochemical storage media with reversible reactions, (d) hydrogen produced by thermochemical cycles and stored in MOF (Metal Organic Framework) based materials for power, heat and hydrogen production on demand.

Achievements in 2014: A kick-off meeting was held in order to establish the main priorities of the project in various activity areas. Working groups have been created in order to identify critical issues for the development of those technologies. For example, the program of work aims to analyzing the feasibility of thermochemical cycles for the production of hydrogen as well as developing new receiver configurations, such as fluidized bed particles receiver (Figure 4.10). Another task concerns the potential integration of thermochemical cycles into solar electricity production at high temperatures.

Furthermore, CIEMAT is exploring new perovskite materials such as LaₓSr₁₋ₓMnₓAl₁₋ₙO₃ and LaₓSr₁₋ₓFeₓAl₁₋ₙO₃ for wo-step water splitting thermochemical cycles. The research efforts are directed towards preparation and synthesis of the materials in the laboratory, testing the perovskites under various reaction conditions, improving the kinetics and reducing the working temperatures [4.15].

Publication: [4.15]

SOLAR FUEL – Mid-temperature Solar Thermochemical Process for Hydrogen Production and Power Generation

Figure 4.9. Sketch of the structural analysis of the metallic CRS-SSPS solar tower test facility.

Figure 4.10. Solar Dish installed at CIEMAT in Madrid to carry out evaluation of the fluidized bed.
Achievements in 2014: The prototype of the direct-heated parabolic trough solar reactor was manufactured [4,16]. The scalable 200 kWth parabolic-trough solar fuel power generation system is now developed. It can be used in West China for electricity generation or applied in the distributed solar energy system. This is further promoted by the National Science and Technology Support Program.

Publications: [4.16]-[4.25]

### 4.3.2 ACTIVITY 6: MARKET PENETRATION (MP)

**Roadmap to Solar Fuels – Strategy for Industry Involvement and Market Penetration**

- **Participants:** PSI (CH), DLR (D), WIS (IL), CSIRO (AUS), NWU (RSA), CSIR (RSA)
- **Contact:** Anton Meier, anton.meier@psi.ch
- **Funding:** SolarPACES ExCo funded project, cost shared: €25,000
- **Duration:** July 1, 2012 - September 30, 2015

**Background:** This SolarPACES Task II Special Activity aims at enhancing industry involvement in solar fuels production and promoting market penetration of solar fuels technologies. Initially, two sun-rich countries—Australia and South Africa—expressed their keen interest to organize workshops with SolarPACES experts presenting to targeted local industry and governments the state-of-the-art and the market potential of the most advanced technologies for solar fuels production. The final outcome will be a country-specific “Roadmap to Solar Fuels” being initiated together with the identified industries and other interested bodies. If successful, such missions may later be extended to other countries involving different industries and various solar fuels or materials production technologies.

SolarPACES has the expertise to develop the solar technology for virtually any process producing solar fuels (hydrogen, syngas, or liquid fuels such as methanol, diesel, and jet fuel) and chemical or material commodities (metals, lime, and cement), as well as to provide solutions for thermo-chemical storage. It is important to spread this message among industry and governments.

**Purpose:** A “Roadmap to Solar Fuels” shall be developed with the objective of facilitating industry involvement and market penetration. In a first step, potential industrial and governmental players in two selected countries—Australia and South Africa—shall be identified and contacted. First-hand information on CO$_2$ mitigation and market potential of solar fuels technologies shall be presented by SolarPACES experts at specific workshops and meetings organized by the corresponding Task II national coordinators (NCs). In a second step, a specific roadmap concept shall be initiated and tailored for each country, showing the most promising options for solar fuels as a result of a screening analysis by the local and external SolarPACES experts, interested industries, and responsible governmental representatives.

**Achievements:** In Phase 1 (2012-2013) of this special Task II activity on solar thermal fuels, the state-of-the-art and the market potential of the most advanced technologies for solar fuels production was presented by external SolarPACES experts to targeted local industry and governments in Australia and South Africa.

**Major events and achievements during Phase 1:**

- Until end of 2012, potentially interested industries and responsible governmental representatives have been identified in both host countries: Australia and South Africa. A “Road Show” (including written documents and oral presentations) has been prepared illustrating the CO$_2$ mitigation and market potential of specific solar fuels (e.g., hydrogen, syngas; liquid fuels such as methanol, diesel, and jet fuel).
- The SolarPACES Workshop “Roadmap to Solar Fuels” was held on 14-15 February, 2013, at the Potchefstroom campus of the North-West University in Potchefstroom, South Africa. The objective of the workshop was to identify potential industrial and governmental players and to create awareness of the potential of solar as an energy source for production of syngas and/or liquid fuels by reforming and gasification of carbonaceous feedstock. SolarPACES experts presented first-hand information on CO$_2$ mitigation and market potential of solar fuels technologies. The workshop was well at-
tended (43 people, including 5 persons from the SolarPACES expert panel) with 8 persons from various government departments, 15 persons from industry and 14 persons from research institutions and academia.

- Australia’s first workshop on developing a Solar Fuels Road Map was held on 23 April 2013 at the Cypress Lakes Resort in the Hunter Valley, Australia. This workshop was jointly supported by the Australian Renewable Energy Agency (ARENA) under the Australian Solar Institute (ASI) funded project “Solar Hybrid Fuels”\(^1\), and also the IEA SolarPACES outreach efforts through the special Task II (Solar Chemistry Research) activity “Roadmap to Solar Fuels”\(^2\), enabling the participation of international experts from Germany, Israel and Switzerland. The SolarPACES experts presented on both solar fuels as well as alternative uses of solar thermal energy, including minerals processing, cement and chemical production. All these processes in their current form produce a significant amount of GHG emissions – thus providing high-temperature process heat from solar energy can assist with Australia’s commitment to reduce GHG emissions. Probably due to the remote location, the workshop was less attended than the previous one in South Africa (27 people, including 6 persons from the SolarPACES expert panel), with 2 persons from government departments, 8 persons from industry, and 11 persons from research institutions and academia.

- As an outcome of this workshop, a review was published on various technologies that can be used to produce solar fuels [4.26]. The review found that most of the technologies have only been developed to the pilot scale, and the most advanced only to a scale of 500 kWh. There is also a lack of key data needed to evaluate the technologies, cost data in particular. However, it is known from experience with CSP that the solar field is a significant proportion of the overall investment cost, around 50%. This means that the conversion efficiency of solar thermal to chemical energy is critical for achieving a cost effective process.

In Phase 2 (2013-2014; extended until 2015), progress in developing a solar fuels roadmap was made in both selected host countries (Australia and South Africa). Contacts with potentially interested industries and responsible governmental representatives have been established. Opportunities for joint projects involving industry, government agencies and international solar research centers have been identified and some of them are expected to be concretized in the near future.

Major events and achievements during Phase 2 (Figure 4.11):

- A critical review of Phase 1 and the preliminary planning of Phase 2 took place at the annual Task II Meeting held in Las Vegas (September 2013).

- In November 2013, a preparatory workshop was held in Newcastle, Australia (mainly attended by Australian researchers), to define the framework for the techno-economic evaluation of CSF technologies. The goal was to determine a cost of fuel for different technologies using a techno-economic model under development at CSIRO.

- On February 27, 2014, a workshop was held in Sydney, Australia (building on the workshop held in April 2013; Phase 1), to discuss the techno-economic model. Three technology case studies were presented: (1) solar reforming of natural gas, (2) solar gasification of coal and (3) solar water/carbon dioxide splitting. 35 participants from industry, government and research were present.

- Following this workshop, a first draft of the “Roadmap to Solar Fuels” was prepared by local and external SolarPACES experts using input from participating industries and other interested bodies.

- On August 20-21, 2014, a “Hybrid Solar/Fossil Energy Conference” was organized in Johannesburg, South Africa, by the Fossil Fuel Foundation in collaboration with North-West University, CSIR and SolarPACES. Solar fuels and high temperature applications were presented by external SolarPACES experts, and the integration of fossil and solar for industry was discussed among about 30 attendees from various government departments, industry, research institutions and academia.

- Following this workshop, a second draft of the full “Roadmap to Solar Fuels” was prepared by local and external SolarPACES experts based on the latest suggestions and preliminary project proposals from the participants.

It was obvious that many attendees of the workshops were not aware of the work being done worldwide on solar thermal fuels. Thus, there is a need to increase the...
awareness of solar thermal fuels, to evaluate the previous R&D work done in this field, and to determine the applicability and feasibility of specific solar fuels technologies in countries like Australia and South Africa, as well as China and many others. Furthermore, it is important to emphasize the economic and political aspects of solar fuels that could be a major export opportunity, as well as providing security of supply.

Although the transition to a hydrogen economy seems remote for countries such as Australia, South Africa, or China, hydrogen is consumed in large quantities for fertilizer manufacture and refining. Therefore, solar production of hydrogen using thermochemical cycles based on metal oxide redox reactions should be considered as long-term option to produce fully renewable solar fuels.

In the near term, the focus should be on syngas, from which one can make a wide variety of synthetic liquid fuels such as methanol, diesel, and jet fuel. Syngas can be produced from steam-reforming of natural gas (NG), oil, and other hydrocarbons, and steam-gasification of solid carbonaceous feedstock such as coal, coke, biomass, bitumen, and carbon-containing wastes. Solar reforming of NG, using either steam or CO₂, and solar-driven gasification have been extensively studied in solar concentrating facilities with small-scale solar reactor prototypes. The first generation of industrial solar reforming and gasification pilot plants using solar tower concentrating systems is coming into operation. Ultimately, solar reforming and gasification are an efficient means of storing intermittent solar energy in a transportable and dispatchable chemical form.

Solar gasification of carbonaceous feedstock is particularly suited for sun-rich countries with abundant domestic coal/coke reserves such as Australia, South Africa, and China. Australia has also large reserves of natural gas but no liquid fuel and, therefore, solar reforming could be an attractive option there. In the end, successful market entry of solar reforming and gasification technologies will depend on the dominant market price of solid feedstock and fossil fuels, as well as on credits for pollution abatement and CO₂ mitigation.

Screening of potential solar fuels processes and a techno-economic evaluation of CSF technologies will eventually lead to a country-specific “Roadmap to Solar Fuels” for Australia and South Africa.

In Phase 3 (2015-2016), a roadmap concept – similar to that developed for Australia and South Africa – shall be initiated and tailored for China. At least two workshops/conferences and several follow-up meetings will be held in China for the preparation of a country-specific roadmap concept, showing the most promising options for solar fuels as a result of a screening analysis by the local and external SolarPACES experts, identified industries, responsible governmental representatives and other interested bodies.

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3 The SolarPACES “Roadmap to Solar Fuels” activity is providing additional international support to the Australian solar research community in developing their own “Solar Hybrid Fuels” roadmap for Australia funded by the Australian Renewable Energy Agency (ARENA). Another goal of the SolarPACES roadmap exercise is to help securing acceptance of solar thermal fuels to be included in the Solar Energy Technology Road Map (SETRM) for South Africa, thus providing a potential funding opportunity for the solar research community and industry in RSA.

Participants: DLR (D), PSI (CH), NWU (RSA), CSIR (RSA), HySA (RSA), Wits University (RSA), DOE (RSA), SANEDI (RSA), TIA (RSA), UP (RSA), US (RSA), Eskom (RSA), Sasol (RSA), Brightsource (RSA), IDC (RSA), PetroSA (RSA), Mintek (RSA)

Contact: Jan van Ravenswaay, jvr@raventechcorp.com

Funding: NWU and SolarPACES ExCo funded project, cost shared: €25,000

Duration: July 1, 2013, - August 31, 2014

Background: South Africa is heavily reliant on fossil fuels for energy. Fortunately it has an excellent solar resource which, through solar fuels or high temperature solar applications offers the potential to reduce carbon dioxide emissions, to increase energy security and to optimize fossil fuel resource use. Solar fuels can be defined as solar derived thermochemical processes and can include energy carriers (hydrogen, synthesis gas and liquid fuels), chemical or material commodities (metals, lime, and cement) or thermo-chemical storage. South Africa is developing a “Roadmap to Solar Fuels” under the guidance of local and SolarPACES experts.

The SolarPACES Hybrid Conference on Solar Fuels and High Temperature Solar Applications (Integration of Fossil and Solar for Industry) was held on 20 and 21 August 2014 in Johannesburg, South Africa.

Purpose: The objective of the conference was to provide a forum in which new concepts in hybridization in energy production will be presented in Southern Africa; To increase the awareness of solar fuels; To determine the applicability and feasibility of specific solar fuels technologies in RSA; To emphasize the economic and political aspects of solar fuels that could be a major export opportunity, as well as providing security of supply; To expose the technical public and potential users to the co-utilization of two energy sources for mutual and economic benefit; and To generate collaboration between two sectors of the energy industry, academia and government.

Feedback: The workshop was well attended (~30 people) with persons from various government departments, industry and research institutions and academia.

<table>
<thead>
<tr>
<th>Date</th>
<th>Activity</th>
<th>Deliverable</th>
<th>Responsible</th>
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</thead>
<tbody>
<tr>
<td>September 2013</td>
<td>Task II Meeting in Las Vegas</td>
<td>Critical review of Phase 1 and preliminary planning of Phase 2</td>
<td>Task II OA NCs RSA / AUS</td>
</tr>
<tr>
<td>November 2013</td>
<td>Workshop Newcastle, Australia; mainly for Australian researchers</td>
<td>Framework for techno-economic evaluation of CSF technology</td>
<td>NC AUS</td>
</tr>
<tr>
<td>February 2014</td>
<td>Workshop Sydney, Australia; Techno-economic assessment</td>
<td>Participants list; Meeting minutes; List of topics/challenges for “Roadmap to Solar Fuels”</td>
<td>NC AUS</td>
</tr>
<tr>
<td>March 2014</td>
<td>Preparation of initial roadmap document</td>
<td>First draft of “Roadmap to Solar Fuels”</td>
<td>C. Sattler (DLR)</td>
</tr>
<tr>
<td>August 2014</td>
<td>Hybrid Solar/Fossil Energy Conference, Johannesburg, South Africa; Industry representatives</td>
<td>Participants list; Conference program; industry contacts; ideas for joint projects</td>
<td>NC RSA Fossil Fuel Foundation</td>
</tr>
<tr>
<td>September 2014</td>
<td>Preparation of draft roadmap</td>
<td>Second draft of “Roadmap to Solar Fuels”</td>
<td>C. Sattler (DLR)</td>
</tr>
<tr>
<td>September 2014</td>
<td>Task II Meeting in Beijing</td>
<td>Critical review of Phase 2 and preliminary planning of Phase 3</td>
<td>Task II OA NCs RSA / AUS</td>
</tr>
<tr>
<td>September 2014</td>
<td>Plenary Session in Beijing</td>
<td>Presentations on “Solar fuels and materials – From research to the market place”</td>
<td>Task II OA C. Sattler (DLR) NCs RSA / AUS Industry (Mitsui)</td>
</tr>
<tr>
<td>March 2015</td>
<td>Preparation of complete roadmap</td>
<td>Final “Roadmap to Solar Fuels” document; Final report to ExCo</td>
<td>Task II OA NCs RSA / AUS</td>
</tr>
</tbody>
</table>

Figure 4.11. Time schedule of “Roadmap to Solar Fuels” (Phase 2) showing activities, deliverables, and responsible persons.
The Local and SolarPACES experts presented on solar fuels related projects, research and development, markets and opportunities to the diverse audience.

The conference covered a good selection of topics that provided the audience an overview of the relative new application of using solar energy to produce solar fuels.

A positive closing discussion was held on the road forward and it was agreed to proceed with the development of the Solar Fuel Road Map for South Africa.

Achievements in Phase 2 (2013-2014): The major achievement of the hybrid conference was the awareness created about the application of solar energy for solar fuels applications. Several participants from industry and government were not aware of work being done worldwide on solar fuels.

Next steps include:

- Follow up meetings will be held with key stakeholders in industry and government to collect requirements for solar fuels related activities as input to the Solar Fuels road map.
- Evaluation of previous and existing solar fuels research and development work and customization for South African applications to understand which opportunities are worth pursuing.

The way forward: Given the excellent solar resource that South Africa has and the potential availability of gas the prospects of solar fuels and HTSA looks very promising. Planning is underway to develop an implementation plan and strategy to proceed with required research and development, human capital development and the establishment of experimental facilities to mature and scale up the envisaged solar fuels technologies for South Africa.

A Department of Science and Technology funded study is underway to determine the best suited Solar Fuels and High Temperature Solar Applications for South Africa to guide future research and development.

References


ence, Kowloon, Hong Kong, December 9-12, 2014.


