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Solar Power and Chemical Energy Systems

SolarPACES

Annual Report 2011

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Deutsches Zentrum für Luft- und Raumfahrt e.V.

Cover picture:
Gemasolar 20 MW Solar Tower Plant, in commercial operation since May 2011, Property of Torresol Energy (© Sener)

Further information on the IEA-SolarPACES Program can be obtained from the Secretary, from the Operating Agents or from the SolarPACES web site on the Internet http://www.SolarPACES.org.

The opinions and conclusions expressed in this report are those of the authors and not of DLR.

Editors

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Foreword

On behalf of SolarPACES, it is a pleasure to present the 2011 annual report.
We are living in challenging times, full of reasons for hope and despair. Never before has humanity been more aware than now of the finiteness of our planet, the negative impact of human activities, and the many advantages of solar and other related renewable energy sources and their potential to satisfy the ever growing energy demand of human societies. But, at this point in time, when, finally, it seems that we all are starting to grasp the vital importance and the urgency to evolve towards a much more sustainable and environmentally friendly world energy system, based upon the extensive use of solar and other renewable energy sources, we are confronted with a financial and economic crisis that is producing devastating and long range consequences at an unprecedented scale.
In this environment, where the competition for financial resources worldwide among competing energy options have never been so intensive and their proponents have never been so aggressive, SolarPACES is more needed than ever to ensure that the Concentrating Solar Thermal Power (CSTP) and Solar Chemistry technologies fulfill their promise to contribute to the improvement of the quality of life of billions of people. The rapid expansion that the CSTP industry is experiencing since 2003 owes much to the unfaltering work of SolarPACES, the international research community that started at the Small Solar Power Systems (SSPS) demonstration project in the 80's. One of the main assets of our organization is its scientific authority: SolarPACES is a neutral, independent organization, fully committed to facilitate, through international cooperation, rational decision making and the success of CSTP and Solar Chemistry technologies.
The annual report gives an overview of the achievements reached by the SolarPACES research community during the year 2011. I wish you a fruitful lecture!

Manuel J. Blanco, Ph.D., Dr. Ing.
Chair, SolarPACES Executive Committee

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1 Report of the SolarPACES Executive Committee for 2011

Christoph Richter
IEA SolarPACES
Executive Secretary

Part 1 of this Report, which gives an overview of results and achievements of the SolarPACES Implementing Agreement in 2011, is submitted to the IEA by the SolarPACES Executive Committee.

Part 2 gives a brief overview on the SolarPACES guiSmo project, aiming at the development of guidelines for CSP plant performance modeling.

The more detailed, technically substantial, non-proprietary information on the progress of SolarPACES projects and their results are given by the five SolarPACES Operating Agents in Parts 3, 4, 5, 6 and 7 of this report. As a new line of activity started in 2011 against a background of growing SolarPACES resources from increased membership, they contain information on activities co-funded by the SolarPACES budget, in Task I regarding Development of Guidelines for CSP Performance Models, Task 3 Development of guidelines for standards for CSP components, Task V Standardizing and Benchmarking of Satellite-Derived DNI-Products and in Task VI for Assessment of CSP+D potential in the MENA area. Detailed reports on these activities are or will be available on the SolarPACES website.

As in previous years, it is also the aim of the Annual Report for the year 2011 to inform member country institutions and partners inside and outside the IEA on progress in developing Concentrating Solar Technologies (CST) for near and long-term competitive markets. In this sense, this report exceeds the formal IEA reporting requirements.

1.1 Objectives, Strategy and Scope

The objectives of the IEA SolarPACES Strategic Plan expanded the role of the Implementing Agreement from one that focused on technology development to one addressing the full range of activities necessary to overcome barriers to large-scale adoption of concentrating solar technology. The primary objectives of the Strategic Plan are to:

1. Support TECHNOLOGY development,
2. Support MARKET development, and
3. Expand AWARENESS of the technology.

In the Strategic Plan, SolarPACES has chosen to expand its outreach and market development related activities in recognition of the impact that increased utilization of concentrating solar power (CSP) systems will have on global climate change; the increased interest by developing countries in SolarPACES; the changing needs of the CSP industry; the revision of the REWP's strategy; and accelerated means of communication through the internet.

IEA SolarPACES *VISION*	Our vision is that concentrating solar technologies contribute significantly to the delivery of clean, sustainable energy worldwide
IEA SolarPACES *MISSION*	Our mission is to facilitate technology development, market deployment and energy partnerships for sustainable, reliable, efficient and cost-competitive concentrating solar technologies by providing leadership as the international network of independent experts
IEA SolarPACES *STRATEGY*	Our strategy is to: • Coordinate and advance concentrating solar technology research by focusing on the next generation of technologies; • Provide information and recommendations to policy makers; • Organize international conferences, workshops, reports and task meetings in order to facilitate technology development and market deployment; • Provide opportunities for joint projects in order to encourage energy partnerships between countries; • Develop guidelines and support standards in order to increase the transparency of the market and reduce risks associated with project development; • Manage the undertaking of independent studies of strategic interest; • Leverage our activities with other IEA implementing agreements and renewable energy organizations.

The IEA SolarPACES Vision, Mission and Strategy are described in the IEA SolarPACES Strategic Plan and were updated at the ExCo Meeting in November 2008 in Almería, Spain, as shown in the box above. The IEA SolarPACES vision and mission statements focus on overcoming the technical, nontechnical, institutional, and financial barriers to the deployment of CSP technologies.

Technology development is at the core of the work of SolarPACES. Member countries work together on activities aimed at solving the wide range of technical problems associated with commercialization of concentrating solar technology, including large-scale system tests and the development of advanced technologies, components, instrumentation, and systems analysis techniques. In addition to technology development, market development and building of awareness of the potential of concentrated solar power are key elements of the SolarPACES program.

The scope of IEA SolarPACES is cooperative research, development, demonstration and exchange of information and technical personnel, for solar power and chemical energy systems. The scope of subjects undertaken is shown in Figure 1.1, by solar concentrating and conversion process.

IEA SolarPACES collaboration extends from concept development in the different solar thermal disciplines, to laboratory research, prototype development, pilot scale demonstrations and final product qualification.

A few examples given here will illustrate the range of the work of SolarPACES. Cooperative development and testing of key solar components, including advanced concentrators and receivers, which has helped reduce the costs and improve the reliability of concentrating solar technology. System tests of pilot-scale plants, such as the 10-MW Solar Two power tower in the United States and the DISS trough system in Spain have demonstrated the performance and reliability data needed to predict commercial plant performance. Similarly, cooperation on system operation and maintenance has led to reduced costs at the commercial Kramer Junction parabolic trough plants in the United States, and will help ensure cost-competitiveness at future concentrating solar power plants. The SolarPACES "START" (Solar Thermal Analysis, Review and Training) team missions have assisted in the introduction of concentrating solar power in developing Sunbelt countries. By sending an international team of experts, independent technical advice has been made available to interested countries including Egypt, Jordan, Brazil, Mexico and Algeria. START missions to Algeria, Egypt, and Mexico have already contributed to the first phase of planning concentrating solar power plants in these countries. In solar chemistry research, where the commercialization goals are more long-term, SolarPACES has succeeded in building and promoting international interest, defining research priorities, and facilitating cooperative international research.

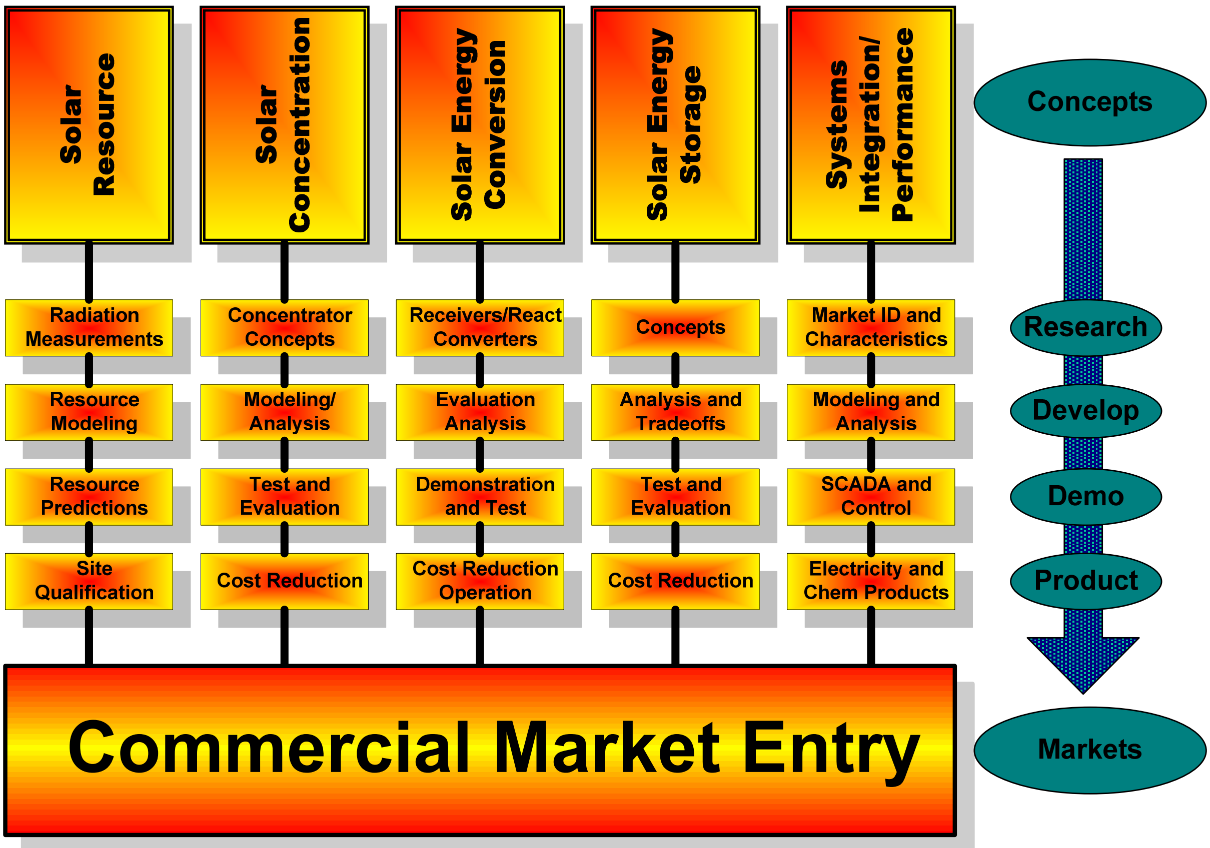

Figure 1.1. Scope of CSP research, development and demonstration work

1.2 *Participation of Countries, R&D Institutions, Utilities and Industry*

As of January 2012, 19 countries, or organizations designated by their governments, and one Sponsor, Mitsubishi, participate in IEA SolarPACES and its different Tasks as shown in Table 1.1. Morocco joint SolarPACES as a new member in 2011.

and utilities. Industry actively participates in SolarPACES Tasks and other activities as partners. Task I, which focuses on CSP systems and is most closely related to market and near-term demonstration projects, is the most prominent example. Industry is responsible for over 50% of the information sharing projects. Apart from task participation, some representatives in the ExCo are from industry (see Table 1.1), and in 2010 the first industrial Sponsor (Mitsubishi) also joined the SolarPACES IA.

The nature of the CSP technologies, with their large

Table 1.1. SolarPACES Membership and Task participation

SolarPACES Membership as of January 2012										
IA participation		Type of Institution				Task Participation				
Country / Sponsor	**Represented by**	**Govt.**	**R&D**	**Ind.**	**Util.**	**I**	**II**	**III**	**V**	**VI**
Algeria	NEAL		x			x		x	x	x
Australia	ASI		x			x	x	x		
Austria	BMVIT	x				x		x		
Brazil	CEPEL		x			x				
China	IEE-CAS		x			x	x	x	x	x
Egypt	NREA	x				x			x	x
European Union	DG-Research, DG Energy	x				x	x	x		
France	CNRS		x			x	x	x		
Germany	DLR		x			x	x	x	x	x
Israel	WIS		x			x	x	x		x
Italy	ENEA		x			x	x	x	x	x
Mexico	IIE		x			x		x	x	x
Mitsubishi (Sponsor)	Mitsubishi Corporation			x		x	x	x	x	x
Morocco	MASEN & IRESEN		x	x		x	x	x	x	x
Republic of Korea	KIER		x			x	x			
South Africa	ESKOM				x	x		x		
Spain	CIEMAT		x			x	x	x	x	x
Switzerland	BfE	x					x	x		
United Arab Emirates	MASDAR	x				x		x	x	
United States of America	DoE	x				x	x	x	x	

Cooperation with industry is a key element in the SolarPACES activities. Those countries that have nominated industry or utilities as the contracting party are represented in the ExCo by representative companies and utilities. Furthermore, the ExCo has invited special guests from industry, utilities, financial institutions and regulatory bodies to most of its meetings. Details are given in the SolarPACES Annual Reports. This has been intensified by introducing a special "Host Country Day" in the ExCo meeting agenda, where energy policy mak ers, utilities and industry are invited to report and discuss the host country's CSP project perspectives.

Industry and utility partners are actively participating in the Tasks and their technical meetings and seminars, as reported in detail in the SolarPACES Annual Reports. Since the announcement of renewable electricity incentive programs in the European Union, industry and utility participation in the task meetings has increased sharply. At the last task meetings, over a dozen private firms were represented. At the last Symposium, about half of the 800 participants came from industry

concentrator fields, receivers and storage systems, implies intensive collaboration with industry in all stages of development, from initial conceptual engineering to prototype development, and to large-scale demonstration. The CSP cost reduction strategy builds on progress in R&D and mass manufacturing by industry. The potential for this has grown exponentially during recent years. In 2010, several new CSP plants have started operation in Spain, the currently most active market with a project pipeline of more than 2 GW. Further potential for increased deployment of CSP is present now in many countries in all five continents, resulting in a total of over 15 GW global CSP capacity in different stages of project development. The Southwest United States alone is expected to see very dynamic growth of CSP plants during the next few years with a cumulative capacity of nearly 10 GW.

In Europe, the Desertec Industrial Initiative (DII) launched in 2009 with growing participation of major companies in Europe and North Africa further increased the potential future market. This initiative intends to prepare the way for the large-scale construction of CSP plants in the great deserts of North Africa and the Middle East plus the necessary interconnection to the power grids in these regions. This extension of Solar Electricity generation capacity along with a future interlinked High Voltage Direct Current (HVDC) Supergrid would allow the endless solar potential of the deserts to be tapped, providing the local electricity supply as well as feeding up to 15% of Solar Electricity into the European Market.

1.3 The SolarPACES Work Program

SolarPACES member (contracting party) activities are carried out through cooperative research, technological development and demonstration, and exchange of information and technical personnel. As the nature of electric power technologies would imply, the parties involved comprise governments, public research institutions, industrial suppliers, electric utilities, and international financing entities. They all cooperate by means of information exchange, formal and informal initiation of joint or national activities – task-shared as well as cost-shared – and also by sharing the costs of mutually agreed-upon activities. In the period under review, the work within IEA SolarPACES was structured in the five main Tasks with a number of Subtasks as shown in Figure 1.2. Tasks V is a collaborative activitie with the Solar Heating and Cooling (SHC) and the Photovoltaic Power Systems (PVPS) Implementing Agreements.. For detailed information on task organization and results of work please refer to the respective chapters in Parts 3 – 8 of this report.

The collaboration that was earlier focused on Research, Development and Demonstration is now increasingly also emphasizing large-scale worldwide deployment. The new Task VI on "Solar Energy and Water Processes and Applications" will provide the solar energy industry, the water and electricity sectors, governments, renewable energy organizations and related institutions in general with the most suitable and accurate information on the technical possibilities for effectively applying solar radiation to water processes, replacing the use of conventional energies.

1.4 Coordination with Other Bodies

SolarPACES is the only agreement and international program working on Concentrating Solar Power technologies. The SolarPACES ExCo represents delegates from national CST (concentrating solar technology) programs with a composite budget of 100 million USD per year and is the only international, multilateral umbrella for CST cooperation.

In Europe and in the US, industry with an interest in CST has associated in their respective industry associations—ESTELA (European Solar Thermal Electricity Association) and SEIA (Solar Energy Industry Association of the USA). SolarPACES is cooperating closely with these associations

Neighboring technologies are general solar utilization and power generation technologies. In this field, SolarPACES is cooperating closely with the International Solar Energy Society (ISES) and its national associations by contributing regularly to their conferences and journals. SolarPACES also contributes regularly to the international power industry conferences like PowerGen and others.

Special acknowledgement is due the European Union and its support of transnational CSP projects within Europe, like SOLHYCO, SOLASYS, SOLREF, SOLZINC, HYDROSOL, SFERA,. The information on these projects has been shared with the non-European SolarPACES partners.

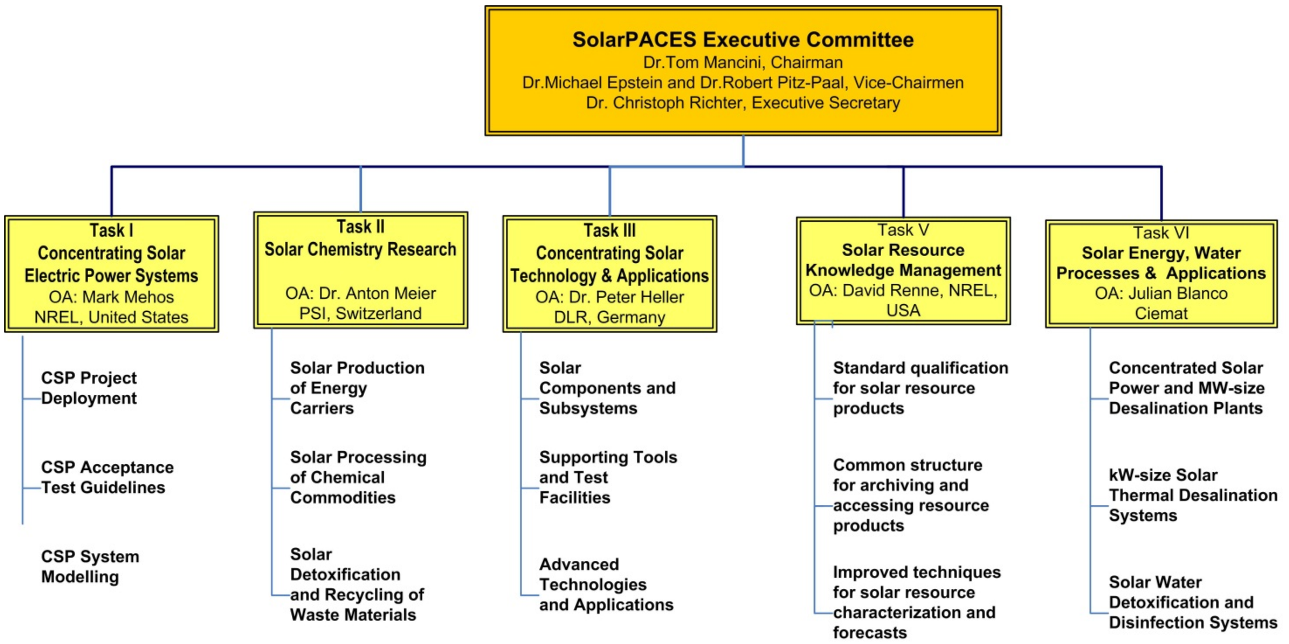

Figure 1.2. Organization of Work within the SolarPACES Task Structure

Proactive cooperation with the IEA Renewable Energy Division has continued and increased, together with other renewable implementing agreements, developing the IEA RD&D priorities, participating in the REWP seminars, dedicated Renewable Energy Workshops and contributing input to IEW publications like the World Energy Outlook (WEO) and Energy Technology Perspectives (ETP). Input and reviewing effort during 2009/2010 was given to the IEA CSP Roadmap, launched in May 2010.

Proactive cooperation is currently ongoing within Task V for "Solar Resource Knowledge Management" with the SHC and PVPS Implementing Agreements.

1.5 Information Dissemination

The key SolarPACES event for information dissemination is the now annually International Symposium on Concentrating Solar Power and Chemical Energy Systems, the international forum where scientists, engineers, users and students learn about the latest advances in concentrating solar technology.

The **17th Symposium**, held from September 20th – 23rd 2012 in Granada, Spain, achieved a participation record with more 1050 participants, including a growing participants from industry in the technical sessions and the exhibition,. The conference was honoured by the Patronage of the Spanish Minister of Science Cristina Garmendia who also spoke in the opening session of the event.

C. Garmendia, then Spanish Minister of Science, in the opening session of the 17th SolarPACES conference in Granada, Spain, 20th September 2011.

SolarPACES publications on CST and sharing national CST publications through SolarPACES-wide distribution lists have become another important means of information sharing**.** The ***SolarPACES Annual Report 2010*** was published and distributed among the SolarPACES members and the participants of the 17th SolarPACES conference, totaling over 1000 interested experts worldwide, giving detailed literature references and contact addresses to encourage further cooperation. SolarPACES participants contributed with input and review to two CSP related IEA publications, the CSP essentials and the CSP roadmap (see www.iea.org/roadmaps). All publications can be found in the library area of the **SolarPACES website** www.solarpaces.org

1.6 SolarPACES Awards

The 16th SolarPACES conference also set the stage for the **SolarPACES Awards** to honor the personal engagement of individuals and institutions that significantly contribute to the deployment of CSP technology. Two types of Awards can be given:

Technological Innovation Award

The Technological Innovation Award for significant innovations leading to more rapid deployment of CSP technology through:

- Performance/cost ratio increase
- Improved manufacturing technology
- Better component lifetime
- Improved environmental profile

The innovation should be realized at least in technical prototype and its characteristics should have been published according to scientific standards.

The 2011 Technology Innovation Award was given to the team of Martin Selig, Gerhard Hautmann and Max Mertins of NOVATEC SOLAR for the lead of development of a solar boiler concept based on linear Fresnel collector technology (NOVA-1).

Technology Innovation Award winners Martin Selig and Gerhard Hautmann of the Novatec Team.

Lifetime Achievement Award

This award honors personal contributions to the successful development and implementation of CSP systems by an individual throughout a major phase of his/her life. Criteria are:

- Acknowledged leadership in research or management in the field of CSP technology
- Long-term commitment to this field
- Promotion of international cooperation

The 2011 Lifetime Award was given to Rainer Aringhoff in recognition of his long contributions to the implementation of CSP technology during his work with Flabeg, Solar Millennium and Dii.

Lifetime Award Winner Rainer Aringhoff during his Award keynote speech

1.7 Meetings and Presentations in 2011

Presentations and Meeting participations in 2010 are summarized below, including Task meetings

For specific task activities please refer to the respective chapters of this report.

February

16th — Task 1 / Task 3 meetings, Granada Congress Center

March

15th-16th — Participation IEA Spring Workshop Renewable Energy

17th — Participation 58th REWP Meeting

April

5th-7th — 80th SolarPACES ExCo meeting, Vienna, Austria

16th — Participation in 2nd IEA communications workshop for Implementing Agreements

June

7th — Session preparation and CSP Overview presentation Intersolar Munich

September

18th — 81st ExCo Meeting, Granada, Spain

19th — Task Meetings

20th – 23rd — 17th SolarPACES Conference, Granada, Spain

October

14th — CSP overview presentation Workshop “Energy management in large research infrastructures” Lund, Sweden

November

29th — CSP R&D presentation CSP today conference, Seville, Spain

2. Guidelines for CSP performance modeling

In 2010, a SolarPACES project was initiated aiming at the definition of guidelines for CSP performance prediction. The overall objective of the project can be summarized as follows:

The SolarPACES project will develop, document and publish guidelines for CSP energy yield analysis with international collaboration.

Contact: Markus Eck, German Aerospace Center (DLR)

Address of contact: Pfaffenwaldring 38-40, 70569 Stuttgart, Germany, markus.eck@dlr.de

Participants: DLR, NREL, Sandia, Cener, Suntrace, Ciemat, Pöyry, Flagsol, Torresol Energy…

Funding: Partly funded by SolarPACES

I = individual member country activities of interest to SolarPACES	
M = member country task-shared activities of interest to SolarPACES	
T = SolarPACES task-shared activities	X
C = SolarPACES cost-shared activities	

Due to the high capacity of solar thermal power plants and large required investment, CSP projects are subject to an extensive project development process. Predicting the energy yield of a CSP plant is a crucial task in this process. Mathematical models predicting the system's energy yield are required to assess single CSP projects (e.g. feasibility or due diligence studies), compare different plant options (e.g. technology, site), optimize technology configuration (e.g. solar field size, storage capacity), investigate the influence of component characteristics (e.g. receiver characteristics), and to assess system performance during commissioning, among other things.

The models used for these tasks differ in complexity and required accuracy, e.g. a model used for project assessment during commissioning has to be more rigorous than a model used for a pre-feasibility study. At the moment, numerous modeling approaches exist, and project developers use their own internal system models and assessment methodology. These models often lack validation, and no standard or benchmark for comparison yet exists for electricity yield analysis of CSP plants. In addition, most current models of CSP system performance do not treat uncertainties inherent in parameters and processes of the complex system. These conditions may fail to alleviate concerns about technology risk and hinder the acceptance of CSP technology by potential investors. To solve this problem, an international working group is being initiated within SolarPACES Task I to define guidelines for performance prediction of CSP plants.

Meanwhile, more than 100 experts have agreed to participate in this project. The project is structured in ten main work packages, as illustrated in table 1 [1].

Table 1. Overview on the work packages

WP 1: Coordination
WP 2: Definition of Structural Framework
WP 3: Physical Component Modelling
WP 4: Consideration of Transient Effects
WP 5: Consideration of Operation Strategies
WP 6: Consideration of Uncertainties
WP 7: Financial Evaluation
WP 8: Meteorological Input
WP 9: Validation and Benchmarking
WP 10: Handbook Energy Yield Prediction

Due to the complexity of the task it was decided to set-up a task-force within the project aiming at the preparation of a draft handbook focusing on parabolic trough power plants using synthetic oil as heat transfer fluid and a two-tank molten-salt thermal energy storage. This draft hand-book will already cover all relevant aspects and thus may serve as a template for the subsequent preparation of handbooks for other trough options or CSP technologies. The results presented in this report are not final represent the present status of the ongoing discussion.

2.1. Current Status

As explained above, the preliminary results presented in this section represent the activities within the guiSmo task-force focusing on state-of-the-art parabolic trough systems. These suggestions have to be discussed within the task-force before editing the hand-book.

Component Modeling

The mathematical modeling of the CSP system itself is a major task within the yield analysis process. To achieve a reliable system model, covering all relevant components of the plant and all relevant physical effects. So far, major components and effects for steady state analysis have been identified (see e.g. [2] and [1]). The current activities focus on the identification of representative model structures for the relevant effects and the assessment and recommendation of prudent default parameter sets for the identified models. Within the project it was decided that the guidelines will not define one specific model structure with one default data set.

This would limit the flexibility required for future developments. Instead of that, the task will be to define reasonable areas of validity for model results and characteristics and develop according plausibility checks.

In [1] the relevant effects for steady-state modeling of all relevant sub-systems have been identified. In the next step these effects have to be defined in greater detail, appropriate modeling approaches have to be assessed, default parameters and areas of validity have to be identified and plausibility checks have to be developed. This task is currently executed within a Master thesis.

Transient Effects

Simulation of concentrating solar thermal power plants using transient models allows obtaining results which are more accurate than those obtained using steady-state models especially during start up and shut down periods. However, the increase in accuracy is not without additional cost: transient models are by far more computationally demanding than steady-state models. This is why it is very important to have a good understanding of when it would be appropriate or necessary to use transient models and when it would be sufficient to use steady-state models. To achieve such an understanding, the influence of transient effects in the operation of the different subsystems of a solar power plant must be analyzed. As a first step in this analysis the results of using three steady-state and four full-transient models to simulate the behavior of the solar field of a parabolic trough plant under diverse transient conditions have been compared. The result for one partly cloudy day is presented in Figure 1.

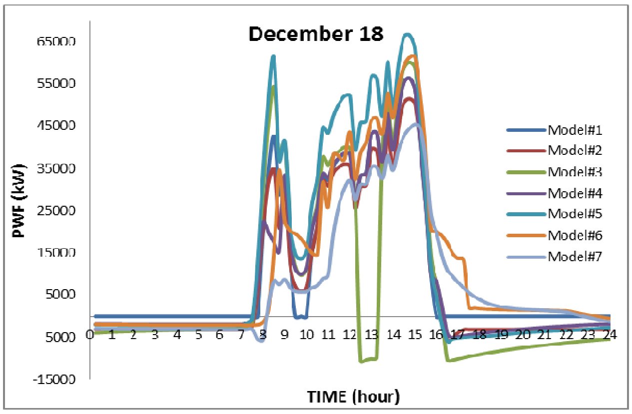

Figure 1: Power to collector fluid (December 18)

According to the benchmarking round conducted, it seems that steady-state models are sufficient to predict the yearly electricity yield as long as the start-up and shut-down process is considered correctly. A transient analysis is required if in-depth information on the detailed intra-day performance of the system is required.

Uncertainties

Uncertainties in modeled parameters and processes are honored using probabilistic methods [3], [4], [5], [6]. Probabilistic methods have the advantage of quantifying the impact of uncertainties on simulated performance metrics by taking into account probability distributions and correlations of inputs quantities. The results of repeated calculations for a large number of input combinations sampled from these distributions are aggregated to form a cumulative density distribution. Therefore, the confidence and likelihood of the simulated metric (e.g., LCOE, net annual energy production) being above or below a particular value or within a given range can be readily assessed and presented. In addition, sensitivity analyses can be used with probabilistic analyses to rank and quantify the most important components, parameters, features, and/or processes that impact the simulated performance. This information can then be used to guide and prioritize future research and characterization activities.

The probabilistic method, which includes (1) sampling from uncertainty distributions, (2) simulating multiple realizations, and (3) performing uncertainty and sensitivity analyses on the results, is illustrated in Figure 2 and will be documented in detail in the guidelines. In particular, this comprises effective sampling methods like Latin Hypercube Sampling and quality criteria such as the validity of confidence evaluating the required sample size.

Within the guiSmo project typical uncertainty distributions for model parameters are being compiled for the different CSP technologies (tower, trough, linear Fresnel, dish) to establish a library of baseline parameters for modelers. Preliminary values illustrating this approach for solar power towers were published in [3].

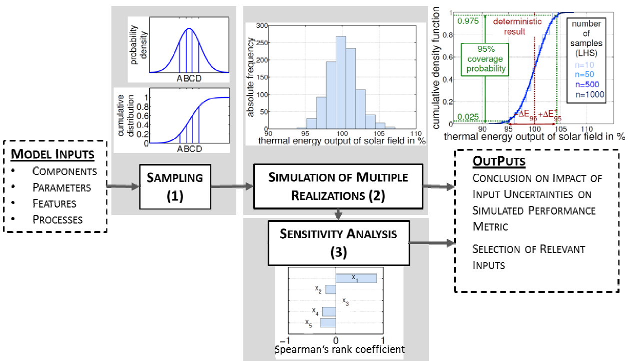

Figure 2: Probabilistic approach to performance modeling

The relevance of the probabilistic approach and the additional information obtained has been demonstrated for parabolic trough and solar power tower plants [3], [4], [5], [6], [7], [8]. Furthermore, probabilistic modeling is essential in the context of performance (acceptance) testing and parameter identification [6]. In this case, long-term plant performance is deduced from short-term testing during which performance parameters are obtained from a series of measurements. The inherent uncertainties associated with the short-term measurements and parameter values are accounted for in the probabilistic modeling.

Key Financial Criteria

There are two principle financing approaches for large scale solar energy projects such as CSP: balance sheet finance and project finance. If a company borrows on its own risk and, together with own funds, passes the funds on to the project, it is considered as balance sheet finance. The risk for the lenders is the creditworthiness of the company, not the project. The company assumes the entire project risk with the full amount of investment cost. As a consequence, there is a natural limit to the repeatability of balance sheet lending: volume and number of investments are limited to the debt capacity of the borrowing company, which can be for example a utility or a large construction firm. As the only financing scheme available, this mechanism would severely constrain the overall sourcing capacity for CSP projects.

Under a project finance scheme, equity and debt providers fund the project itself. The project is set up as a separate as it is called "*Special Purpose Vehicle*", or SPV. Such SPV needs to be funded with equity and debt to be able to purchase the power generating assets, usually from a turn-key provider (*Engineering Procurement Construction* firm or *EPC*). Once in operation, the SPV, which has turned into a real power plant now, pays the debt service to banks (*Lenders*) and dividends to the shareholders/investors. The lenders provide long term debt to the project against the security of the shares and assets of the project and the equity investors can limit their risk to the equity portion (usually a 25-30% share of overall investment cost). This structure is called *non-recourse*, because the lenders supposedly do not rely on other security than the project itself. The equity providers limit their exposure in liquidity and risk principally to their equity injections. Hence, non-recourse project financing schemes have a number of advantages: they allow investors to limit their liquidity requirements, share the risks with lenders and improve equity returns. In the larger context, project finance allows to tap large bank and debt capital markets. Last but not least, project financing enables financial investors to enter the landscape, such as infrastructure and pension fund. In addition, project financing schemes can help develop or tap domestic bank and capital markets in developing countries and emerging markets.

The key financial figures and mechanisms for equity and debt providers under project financing schemes are being defined and described, focusing principally on the quantitative criteria of the project financing realm. Principal financial parameters like Capital Expenditure (CAPEX), Operational Expenditure (OPEX), Investment Criteria such as Net Present Value (NPV), Internal Rate of Return (IRR) Debt Ratios and figures (Debt Equity Ratio, DE Ratio), Debt Service Coverage Ratio, DCSR are being described and it is explained to which extend these are being used to structure and evaluate the financing structures of projects.

Building a financial model and assuming a typical non-recourse financing structure for CSP plants allows to illustrate the mechanisms and interdependencies, in particular in a number of scenarios to explain the trade-offs. Of particular interest is the interaction with the key output data of the solar energy yield models and technological assumptions, as the impact of the energy yield models and technical cost assumptions and their sensitivity becomes transparent. These scenarios are intended to clearly identify the most sensitive factors and hence help set priorities in further iteration and optimization of technical models and concepts.

Meteorological Input

Ho and Dobos [8] concluded DNI often is the greatest source of uncertainty for calculating yields of CSP. On first sight the annual average or sum seems to be most important. Chhatbar and Meyer [9] showed that also the frequency distribution of DNI has significant influence on energy yields. For CSP yields and plant design it plays an important role whether low DNI is more often caused by short interruptions due to clouds or higher turbidity, e.g. by dust. Thus, much care must be taken for preparing realistic DNI input data representing well the typical weather patterns at sites to be investigated.

In guiSmo the Work Package on meteorological input defines the respective parameters, prepares sample time-series data and estimates their uncertainties. Goal is also to define common formats for the input of CSP-specific meteorological input data. The file formats should allow including proper documentation of meta-data, good traceability for due diligence, and easy file handling for comfortable I/O into performance simulation models. For better considering transient effects the time resolution of the input files needs to increase at least to 15 min [10]. If possible likely even higher time resolutions up to 1 min could be required to estimate yields of solar thermal power plants with high sensitivity to irradiance variation in broken cloud cases. It should be evaluated whether variable time resolutions would make sense, e.g. high resolution during variable periods and lower resolution during periods with almost constant DNI or during night-time. For practical reasons the format should be capable of covering only short time periods like single days for detailed analysis, but also multiple years for assessments of the inter-annual variability of CSP yields. Up to know most input formats used for CSP performance simulation are based on ASCII-text-files. For multi-year files in high time resolution such file-formats could be more than 100 MByte big. To make it easier to handle it is recommended to check the applicability of much smaller-packing well-established binary file-formats such as netCDF or HDF for this application.

Building on earlier recommendations [11], [12] for bankable solar resource assessments for CSP the works also should clearer define what is recommended for such expert opinions. Goal is to reach the high quality appropriate to the sensible topic of DNI in view of the high expenditures for a CSP-plant to be built on a certain site. According to Meyer et al. [11] on site meteorological measurements are necessary, which need to be well calibrated. These should be well maintained and need thorough quality checks before applications. To achieve the required long-term time-series of at least 10 years usually the measurements are combined with site-specific satellite-derived DNI data. The longer the overlap the better is the quality of the adapted satellite data, but usually 1 year of measurements leads already to relatively good results [13]. The more years are covered by the full time-series the lower drops the remaining contribution to the overall uncertainty.

2.2. Conclusion and Outlook

This report gives an update on the present status of the SolarPACES project guiSmo. Within the project it was decided to set-up a task-force aiming at the preparation of a draft handbook focusing on parabolic trough power plants using synthetic oil as heat transfer fluid and a two-tank molten-salt thermal energy storage. This draft hand-book will already cover all relevant aspects and thus may serve as a template for the subsequent preparation of handbooks for other trough options or CSP technologies.

So far, first proposals for appropriate definitions of relevant effects and the according modeling approaches have been developed. Relevant operation strategies for the considered CSP system have been identified and a benchmarking of several transient and steady-state simulation tools has been conducted to identify the influence of transient effects on the electricity yield. This study suggests that most transient effects may have a significant influence on the present status of the plant but only a minor effect on the yearly electricity yield. Nevertheless, transient effects such as the start-up and shut-down have to be considered in any case. Furthermore, a first methodology for the consideration of uncertainties is presented and visualized. Finally, an intensive discussion has started on the definition of quality criteria for useful meteo-data and the recommendation and definition of appropriate financial assessment criteria.

The results presented in this report are not final but meant as a basis for further discussion within the guiSmo community.

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3. Task I: Solar Thermal Electric Systems

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3.1 Nature of Work & Objectives

Task I addresses the design, testing, demonstration, evaluation, and application of concentrating solar power systems, also known as solar thermal electric systems. This includes parabolic troughs, linear Fresnel collectors, power towers and dish/engine systems. Through technology development and market barrier removal, the focus of SolarPACES Task I is enabling the entry of CSP systems into the commercial market place. The component development and research efforts of Task III (see Part 5 of this report) logically feed Task I as new components become parts of new systems. In return, the results of this Task I provide direction to Task III on new component needs.

3.2 Organization and structure

The Task I Operating Agent is responsible for organization and reporting of Task I activities. Due to the desire of CSP developers and other stakeholders to promote and increase the financeability of CSP projects, Task I has focused recently on two primary subtasks, 1) the development and population of an international project database for commercial CSP systems under operation, construction, or development and 2) the development of acceptance test procedures and standards for CSP systems. A third subtask, the development of best practice guidelines for modeling CSP systems, received funding from SolarPACES and initiated work on this topic in 2010. Each of these three subtasks will be described more fully later in this chapter.

3.3 Status of the Technology

Between 1985 and 1991, some 354 MW of solar trough technology were deployed in the U.S. in southern California. These plants are still in commercial operation today and have demonstrated the potential for long-term viability of CSP. Worldwide, CSP has seen a resurgence of interest for markets in the USA, Spain, and the Middle East and North Africa (MENA) region. In the United States, 514 MW of CSP were in operation at the end of 2010 with an additional 1,350 MW under construction and 4,000 MW under development. Spain has 1,582 MW of commercial CSP generation and an additional 774 MW under development (Status August 2012) to come on-line during 2012 and 2013.

While CSP continues to gain market share worldwide, reductions in the installed cost for utility-scale photovoltaic systems have resulted in fierce competition between the two technology options with PV now undercutting the capital and energy price for CSP systems. The ability of CSP plants to provide high value firm, dispatchable power through the use of thermal storage or hybridization with fossil fuels has become increasingly important. Recent analyses published in the U.S. indicate that as the penetration of PV systems increases over time, the capacity value of this intermittent resource will diminish considerably (essentially to zero) while the value of CSP systems with storage will remain at high levels.

The predominant CSP system today is the **parabolic trough** technology. A parabolic trough system consists of long parallel rows of curved reflectors that focus sunlight onto a receiver pipe. A heat-transfer fluid (HTF) circulated through the pipes collects the solar heat and transfers it to a central power block where the heat is used to produce steam. The steam drives a conventional steam-Rankine turbine generator. 14 trough plants in Spain are now operating with indirect molten-salt storage. Annual and design point efficiencies for the current generation of parabolic trough plants operating or under construction continue to increase and are expected to be greater than 15% and 23% respectively, based on improved performance of mirrors and heat collection elements. Advanced parabolic trough systems designed to operate at higher temperatures could include direct steam or molten salt as heat transfer fluids in place of today’s synthetic oils. If successfully implemented in commercial plants at a large scale this would result in an increase in operating efficiency and, for molten salt systems, a reduction in thermal energy storage cost.

Linear Fresnel systems have the potential for a lower capital cost than systems based on parabolic mirrors because they use flat rather than deeply curved mirrors, and the mirrors are located close to the ground, giving them a lower wind profile. However, linear Fresnel systems have lower operating efficiencies than parabolic trough systems. It is still unclear whether the lower upfront capital cost will outweigh the lower operational efficiency however the advent of construction of several large systems will provide cost and performance data to support cost of energy calculations. To date, most research on linear Fresnel systems has focused on the use of steam as the heat-transfer fluid although some efforts are underway to investigate molten salt as an alternative to steam.

In a **power tower** system (also called a central-receiver system) a field of two-axis-tracking mirrors, called heliostats, reflects solar energy onto a receiver that is mounted on top of a centrally located tower. Similar to parabolic troughs, an HTF heated in the receiver is used to generate steam, which, in turn, is used in a conventional turbine generator to produce electricity. Some power towers use water/steam directly as the HTF. Other designs use molten nitrate salt because of its superior heat-transfer and energy-storage capabilities. Central-receiver systems typically operate at higher temperatures than parabolic troughs, with superheated steam temperatures of 550°C for proposed steam and molten-salt systems. As with parabolic troughs, central-receiver systems can be integrated with thermal storage. However, the amount of thermal storage depends on the HTF used in the receiver. Direct-steam receivers offer limited storage capacities, typically less than one hour, due to the high costs associated with storing high-temperature steam. Systems based on molten-salt receivers integrated with thermal storage have been demonstrated at a pilot-scale and 2011 marked the successful operation of the first commercial molten salt plant, Gemasolar, a 20MW system with 15 hours of thermal energy storage. Annual efficiencies of molten salt towers are projected to be somewhat higher than those projected for current oil-based parabolic trough systems.

A **dish/engine** system mounts an individual heat engine at the focal point of a two-axis-tracking parabolic dish. Unlike the other CSP technologies, dish/engine system do not use steam generators, but rely on smaller Stirling or Brayton engines as the power-conversion device. Dish/engine systems have demonstrated peak efficiencies greater than 30%. The projected annual conversion efficiency is 24%. At present, most effort is in developing a commercial product.

Thermal energy storage is an important attribute of CSP. Low levels of storage - 30 minutes to 1 hour of full-load storage - can ease the impact of thermal transients such as clouds on the plant and of electrical transients to the grid. However, the most significant attribute of thermal storage is that it can significantly increase the energy and capacity value as compared to equivalent systems without storage, helping offset the variability in other renewable generators and allowing the dispatch of solar power after sunset.

Considerable research is underway to investigate **Advanced Power Cycles** that are applicable to future high-temperature CSP systems. In general, thermodynamic cycles with higher temperatures will perform more efficiently. Of course, the solar collectors that provide the higher-temperature thermal energy to the process must be able to perform efficiently at these higher temperatures. Considerable development is taking place to optimize the linkage between solar collectors and higher-temperature thermodynamic cycles. The most commonly used power block to date is the sub-critical steam Rankine cycle. Power towers and dishes are capable of reaching the upper limits of existing fluids (around 600°C for present molten salts) for current sub-critical steam-turbine cycles, and they can also provide the temperatures needed for higher-efficiency cycles such as gas turbines (e.g., gas Brayton, supercritical steam, and supercritical CO_2 cycles).

3.4 Reported Task I activities

The focus of Task I efforts has continued on development of the international project database for CSP systems as well as facilitating discussions related to the development of procedures and test standards for CSP systems. A third activity, the development of best practice guidelines for modeling CSP systems has been starting during 2011. Each of these efforts is described briefly below.

3.4.1 Performance Acceptance Test Guidelines for CSP Solar Fields

Participants: NREL (US), K&A (US)

Contact: Mark Mehos, mark.mehos@nrel.gov

Funding: USDOE ($100K FY11), cost share

Duration: April 2008 – December 2011

Background: This activity was initiated in 2008 following the 2008 14th Biennial CSP SolarPACES Symposium held in Las Vegas, NV. Those attending a Task I meeting at that venue expressed interest in defining a program for developing procedures and test standards for CSP systems with an initial emphasis on procedures for acceptance testing of parabolic trough solar fields. In March 2009, a preparatory workshop was jointly hosted by NREL and DLR in Golden, Colorado in conjunction with Task III to further define the activity. The objective of the preparatory workshop was to organize and to gather expert opinions on the subject of testing and standards in preparation for a follow-on open workshop coincident with the 2009 SolarPACES Symposium held in September 2009 in Berlin.

Subsequently NREL, through a contract with Dr. David Kearney, supported an effort to develop preliminary guidelines for acceptance testing of parabolic trough solar fields. An acceptance test protocol Advisory Committee, consisting of a panel of international experts, was formed to help guide the effort. The committee consisted of representatives from Worley Parsons, NextLight, Fluor Power, Acciona Solar Power, Abengoa Solar, Solar Millennium, Flagsol, Arizona Public Service, NV Energy, Black and Veatch, R.W. Beck, and Fichtner Solar.

In parallel with this activity, a recently formed American Society of Mechanical Engineers (ASME) committee is working on "Performance Test Code[1] 52 – Concentrating Solar Power Plants" that should supplant this Guideline when completed within several years.

The first full draft of the guidelines was distributed for review to Task I participants and a large group of industry stakeholders in early September 2010, and a paper outlining the status of the project was delivered at SolarPACES 2010 in Perpignan, France in late September [Ref. 3.1]

[1] Often abbreviated as PTC.

Objectives:

The objective of this activity is to develop interim guidelines for acceptance test procedures that can yield results of a high level of accuracy consistent with good engineering knowledge and practice. While the initial set of guidelines were specifically written for parabolic trough collector systems with a heat-transport system using a high temperature synthetic oil, the basic principles are relevant to other CSP systems and extension to power tower technology began in 2011.

Achievements in 2011:

Based on the reviews of the draft Guidelines from 2010 activities, the final version of the parabolic trough Guidelines was distributed in May 2011 as an NREL report [Ref. 3.2]. This report has received broad interest among stakeholders in the CSP community. A 2011 SolarPACES paper [Ref. 3.3] summarized the final Guidelines.

With the trough work as a foundation, an activity was initiated to develop similar Guidelines for Power Tower systems. To this end a Power Tower Advisory Committee was formed to gain active expert input during the Guideline development. The primary purpose of the Advisory Committee is to provide knowledgeable guidance, critique and continuity over the course of the project, with membership oriented towards technical input from the EPC, technology provider, and independent engineer sectors. The committee membership is comprised of expert representation from the U.S., Spain and Israel, most of whom overlap with the power tower committee of the ASME PTC 52 activity.

Two Advisory Committee meetings were held (in August and November, 2011) to address the issues of test boundaries, thermal stability in the receiver, test conditions and methods, and the treatment of both water-steam and molten salt tower configurations. Preparation of the compete draft "Power Tower Guidelines for Performance Acceptance Testing" for review by a large number of stakeholders will take place in the first half of 2012. A draft summary of the scope and early conclusions of that work is given below.

Summary of Power Tower Acceptance Test Guidelines:
Prior to commercial operation, large solar systems in utility-size power plants need to pass a performance acceptance test conducted by the engineering, procurement, and construction (EPC) contractor or owners. In lieu of the present absence of ASME or other international test codes developed for this purpose, the National Renewable Energy Laboratory has undertaken the development of interim guidelines to provide recommendations for test procedures that can yield results of a high level of accuracy consistent with good engineering knowledge and practice. The Guidelines contained here follow the general approach of the earlier NREL report on parabolic trough collector fields, but in this case are specifically written for power tower[2] solar systems comprised of a heliostat (reflector) field directing the sun's rays to a receiver (heat exchanger) on a high central tower. The working fluid in the tower can be molten salt, water-steam, or air, each with its own particular attributes.

The fundamental differences between acceptance of a solar power plant and a conventional fossil-fired plant are the transient nature of the energy source and the necessity to use a detailed performance projection model in the acceptance process. These factors bring into play the need to establish methods to measure steady-state performance, comparison to performance model results, and the reasons to test, and model, multi-day performance within the scope of the acceptance test procedure. The power block and balance-of-plant are not within the boundaries of this Guideline. The current Guideline is restricted to the solar thermal performance of power tower systems, and has been critiqued by a broad range of stakeholders in concentrating solar power development and technology.

The solar system boundary is defined as shown in Fig. 1 wherein the inputs are the solar resource, inlet working fluid, and internal plant parasitic power, and the sole output is the thermal energy contained in the working fluid. Configurations with water-steam and air working fluids are direct systems in which heat is added directly in the receiver to the working fluid of the power cycle. In a molten salt configuration heat is added indirectly to a molten-salt heat transfer fluid and subsequently transferred to the power cycle working fluid, though this heat exchange occurs outside of the test boundary.

The scope of these Guidelines does not include a thermal storage system.

Performance acceptance tests are to be conducted with accuracy defined in clearly stated procedures agreed upon between the parties involved. These Guidelines deal with issues specific to utility-scale power tower solar systems. However, applicable performance test codes (PTCs) developed by ASME for other types of energy systems have very useful information for developing a detailed test plan, and are appropriately cited in these Guidelines. For example, applicable PTCs provide a general framework and information about instrumentation, data acquisition, data reduction, testing procedures, uncertainty levels, and test reports.

[2] Also referred to as central receiver systems.

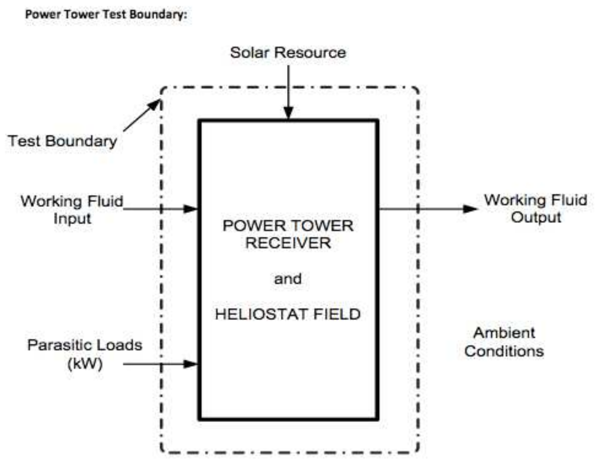

Figure 1. Schematic of solar system boundary and performance model

Two primary types of test runs are to be conducted. The first – the Short-Duration Steady-State Thermal Power Test – measures the thermal power output and thermal efficiency of the solar system under clear-sky conditions over a short period during which thermal equilibrium and stable steady-state conditions exist, and compares the measured results to performance model projections for those parameters. The purpose of this test is to determine with minimal uncertainty whether the solar field is producing thermal power at the expected level given the present irradiation and ambient weather conditions. Important issues related to both stabilized test conditions and thermal equilibrium and are discussed in the Guidelines. If required by agreement, a power test is run at full output to prove the ability to reach design capacity. Power Test durations are typically run in fractions of an hour.

The second – the Long-Duration Production (or Reliability) Test – is a multi-day test that gathers continuous thermal energy output and compares the results to projections from a performance model. Both clear-sky and partly cloudy conditions are acceptable. Additionally, the functionality of the solar system can be observed with regard to such items as daily startup, normal operation, and shutdown. Production Test durations are typically on the order of 10-30 days.

To recapitulate, the primary objectives of the test series are the following:

a. Power Test – a short-term test to measure solar thermal power output
b. Efficiency Test – measurement of solar thermal efficiency as part of the Power Test
c. Production Test – a long-term test to measure performance over an extended period
d. Capacity Test – a Power Test conducted to verify design-point solar thermal power a suitable test conditions
e. For each test, the results are compared to performance model projections for the appropriate test conditions.

Test methods are provided in the report for both the short-term thermal power test and multi-day energy production test. Of special importance are the criteria that must be satisfied by the short-term power test. The recorded data can be viewed as having two components - the actual test measurements and the uncertainty interval associated with those measurements and other test conditions. Both are closely examined within these Guidelines, especially the magnitude of uncertainty in the results, and recommendations made on acceptable limits.

For the short-term power test, the solar system must be in a stable thermal condition (thermal equilibrium) and stable test condition (thermal power measurement) prior to testing. This requires stable characteristics in the solar resource (Direct Normal Insolation) and other conditions. Once thermal equilibrium and test condition stability have been reached, the criteria for valid thermal power and efficiency measurements (i.e., valid test runs) are primarily based on the level of uncertainty in the test results calculated using standard practice. Systematic uncertainties are the dominant consideration.

However, and very importantly, it must be recognized that the purpose of these Guidelines is to provide information so that the testing parties can settle on project-specific, agreed-upon criteria and other test issues important to the overall purpose of the tests. For any given project, the performance acceptance tests will be conducted in accordance with a Test Plan written by the testing parties that may or may not include the recommendations made in this document. The intent of these Guidelines is to provide insights into the issues and test methods that are critical to formulating a valid Test Plan, and to lay the groundwork for accurate test results.

Publications (see References)

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3.4.2 guiSmo – Guidelines for CSP performance modeling

I = individual member country activities of interest to SolarPACES	
M = member country task-shared activities of interest to SolarPACS	
T = SolarPACES task-shared activities	X
C = SolarPACES cost-shared activities	

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Due to the high capacity of solar thermal power plants and large required investment, CSP projects are subject to an extensive project development process. Predicting the energy yield of a CSP plant is a crucial task in this process. Mathematical models predicting the system's energy yield are required to assess single CSP projects (e.g. feasibility or due diligence studies), compare different plant options (e.g. technology, site), optimize technology configuration (e.g. solar field size, storage capacity), investigate the influence of component characteristics (e.g. receiver characteristics), and to assess system performance during commissioning, among other things.

The models used for these tasks differ in complexity and required accuracy, e.g. a model used for project assessment during commissioning has to be more rigorous than a model used for a pre-feasibility study. At the moment, numerous modeling approaches exist, and project developers use their own internal system models and assessment methodology. These models often lack validation, and no standard or benchmark for comparison yet exists for electricity yield analysis of CSP plants. In addition, most current models of CSP system performance do not treat uncertainties inherent in parameters and processes of the complex system. These conditions may fail to alleviate concerns about technology risk and hinder the acceptance of CSP technology by potential investors. To solve this problem, an international working group is being initiated within SolarPACES Task I to define guidelines for performance prediction of CSP plants.

guiSmo – Guidelines for CSP performance modeling

In 2010, a SolarPACES project has been initiated aiming at the definition of guidelines for CSP performance prediction. The overall objective of the project can be summarized as follows:

The SolarPACES project will develop, document and publish guidelines for CSP energy yield analysis with international collaboration.

Meanwhile, more than 100 international experts have agreed to participate in this project. The project is structured in ten main work packages.

1. Coordination
2. Definition of Structural Framework
3. Physical Component Modelling
4. Consideration of Transient Effects
5. Consideration of Operation Strategies
6. Consideration of Uncertainties
7. Key Financial Criteria
8. Meteorological Input
9. Validation and Benchmarking
10. Handbook Energy Yield Prediction

So far the structural framework for a common methodology for CSP performance prediction has been defined. This framework covers topics like the definition of a general nomenclature or a methodology for structuring systems into sub-systems valid for all CSP systems [1]. Furthermore, the interfaces of the different sub-systems have been defined in detail. Based on a detailed benchmarking campaign for parabolic trough system models, relevant effects to be considered for the modeling of all relevant sub-systems have been identified [2].

In work package 10 a WiKi system was implemented for sharing information and preparing a first draft of a latter hand-book [3].

Currently, a comprehensive methodology for parabolic trough plants with thermal storage system is under development. One focus of this activity is the collection, comparison and assessment of conceivable modeling approaches for all relevant sub-systems. Another focus is on the definition of meaningful financial assessment criteria and the unique description of the principle operation strategies. More information on the project can be found on the project homepage [4].

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[3] https://modeling-guidelines-wiki.solarpaces.org/home

[4] http://www.solarpaces.org/Tasks/Task1/modelingguidelines.htm

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 thermochemical processes and to demonstrate their technical and economic feasibility at an industrially scale:

- *Production of energy carriers*: conversion of solar energy into chemical fuels that can be stored long-term and transported long-range. During this term, special focus is on solar thermal production of hydrogen and syngas.
- *Processing of chemical commodities*: use of solar energy for processing energy-intensive, high-temperature materials.
- *Detoxification and recycling of waste materials*: use of solar energy for detoxification and recycling of hazardous waste and of secondary raw materials.

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 2011, we welcomed three new NCs: Robbie McNaughton from CSIRO for Australia; Pietro Tarquini from ENEA for Italy; and Nathan Siegel from Bucknell University for USA. We gratefully acknowledge the service provided by the former NCs: Keith Lovegrove, Australia; Paolo Favuzza, Italy; and Alan Weimer, USA. 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 economical feasibility. Task II is continuously striving to stimulate public awareness of the potential contribution of solar chemistry to clean, sustainable energy services.

4.2 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 2011, 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 2011, solar chemistry research was presented at two major international conferences:

- *17th SolarPACES Conference*, Granada, Spain, September 20-23, 2011: 16 papers were presented on solar fuels and chemical commodities.
- *ASME 5th Int. Conf. on Energy Sustainability*, Washington DC, USA, August 7-10, 2011: 14 technical papers and additional 14 oral presentations were given in five solar chemistry sessions.

Complementary activities have been pursued in the frame of the International Energy Agency Hydrogen Implementing Agreement (IEA-HIA) Task 25 on High Temperature Processes for Hydrogen Production [4.1].

The OA has served as a contributing author to the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation, describing solar fuel technologies that convert solar energy into chemical fuels, such as hydrogen, synthetic gas and liquids [4.2].

In the following, the most important achievements in 2011 of Task II related projects are summarized with updated information about project participation, objectives, status, and most relevant publications.

4.2.1 SOLAR PRODUCTION OF ENERGY CARRIERS

Solar-Enhanced Fuels for Electricity and Transport

Participant: CSIRO (AUS)

Contact: Glenn Hart, glenn.hart@csiro.au

Funding: Asia-Pacific Partnership on Clean Development and Climate (APP);
CSIRO Energy Transformed Flagship:
$AU 9,855,503

Duration: March 2008 - June 2012

Background: CSIRO is demonstrating a concept for integrating solar thermal energy and fossil fuels for advanced power generation and other applications. It has the potential to achieve high thermal efficiencies and greatly reduced carbon dioxide emissions. It uses solar energy to reform methane-containing gases with steam to generate a mixture of CO_2 and H_2 (Figure 4.1). Carbon dioxide is recovered for disposal and hydrogen is used for power generation. A variation of the concept, involving only the reforming of CH_4 with steam and/or CO_2, can produce a range of solar-enriched fuels and synthesis gas (mainly H_2 and CO) that can be used as a chemical feed stock or a metallurgical reducing gas.

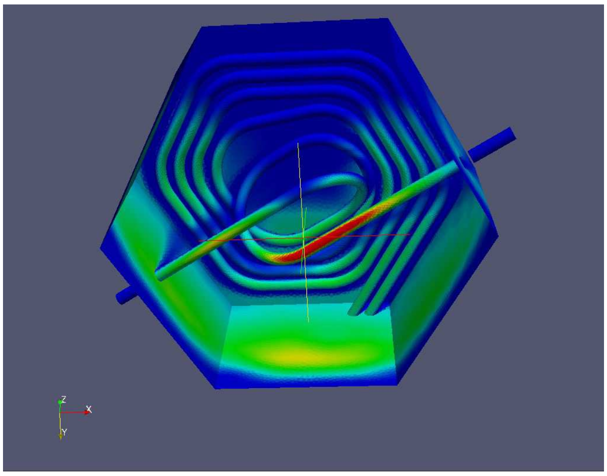

Figure 4.1. CSIRO's 200 kW_{th} reforming reactor, showing expected flux distribution at noon.

Purpose: The research objective is (1) to design, test and build a modular solar concentrating thermal system, which will convert water and methane into hydrogen and carbon monoxide, and (2) to demonstrate the technical and economic feasibility of solar enhanced fossil fuels for electricity and transport.

Achievements in 2011: The focus of this year's work has been on the development of a 600 kW_{th} decoupled natural gas steam reformer. The new process uses a solar thermal driven air receiver to provide the heat to a shell and tube heat exchanger. Air is circulated to the solar receiver where it is heated to 850°C before entering the shell side of the heat exchanger. The tube side houses the reforming catalyst and is where the reaction will occur. The syngas from the reactor is fed to a second shell and tube heat exchanger where it is cooled with the incoming water/steam for the syngas reaction.

The new reactor vessel and heat recovery systems are currently being manufactured and on sun testing of the process is expected in mid 2012.

This project has also seen the completion of a program of steam reforming catalyst development. The focus of this activity was to develop catalysts that are more suited to cyclic operations, operate at lower temperatures and reduced steam to carbon ratios. Excellent results have also been achieved in producing catalyst with a higher reactivity than commercial catalyst.

MET.I.SOL – Methane/Hydrogen Mix Produced by Solar Thermochemical Cycles and On-Board Storage

Participants: FIAT Research Centre (I), ENEA (I), University of Rome "La Sapienza" (I), University of Turin (I), Società Energetica Lucana, FN (I), et al.

Contact: Pietro Tarquini, pietro.tarquini@enea.it
Giampaolo Caputo,
giampaolo.caputo@enea.it

Funding: Ministry of Environment (I): € 1,200,000

Duration: February 2011 – February 2013

Background: The MET.I.SOL project is a national initiative involving ENEA, FIAT Research Centre, two Italian Universities, an Energy Company of Basilicata and other Italian SMEs (Figure 4.2). The project is financed by the Italian Ministry of Environment for the promotion of energy efficiency and renewable energy sources in urban areas.

Purpose: The first task is the development of a low temperature (≤ 530°C) steam reformer of natural gas or biogas to produce a mix of hydrogen and methane for I.C. engines. The reformer will be fed with solar heat stored by means of molten salts. The second task is the development and testing of on board low weight storage systems containing a mix of H_2 and CH_4.

Achievements in 2011: In the initial stage of the project, activities for testing commercial catalysts operating at low temperature have started at the ENEA laboratories. Research and development of new specific catalysts, studies of the heat exchange with molten salts, and the pre-design of a chemical reactor are in progress at the Universities of Turin and Rome.

SYNPET – Hydrogen Production by Solar Steam-Gasification of Petcoke

Participants: PDVSA (Venezuela), CIEMAT (E), ETHZ/PSI (CH)

Contact: Alfonso Vidal, alfonso.vidal@ciemat.es
Juan C. de Jesús, dejesusjc@pdvsa.com
Aldo Steinfeld, aldo.steinfeld@ethz.ch

Funding: PDVSA-CIEMAT-ETHZ: $ 8,300,000

Duration: January 1, 2003 – June 30, 2012

Background: PDVSA, CIEMAT and ETHZ are conducting a joint project with the goal to develop and test a 500 kW_{th} solar reactor for the steam gasification of petcoke – petroleum derivatives and residues – to produce hydrogen and syngas using concentrated solar radiation. The modeling and engineering design of the solar reactor as well as the results of preliminary experimental campaigns have been summarized in previous SolarPACES reports. CIEMAT managed the construction and installation of the 500 kW_{th} solar gasification plant at the 40 m platform of the SSPS/CRS tower at the Plataforma Solar de Almería (PSA).

Purpose: The project aims at experimentally demonstrating the technology for gasifying heavy crude oil solid derivatives – such as petcoke – in a solar pilot reactor.

Achievements in 2011: The performance evaluation of the 500 kW_{th} solar gasification plant on the SSPS/CRS tower was further advanced. Considerable progress has been made in identifying and solving key technical problems related to the front part of the solar reactor, namely the window, the cone, and the aperture.

The design and fabrication of transparent windows for solar thermochemical reactors – applicable for large focal spots in central receiver systems – represent a technical challenge. Within this project, an innovative design of a segmented quartz window with an inner diameter of 1340 mm has been developed. It consists of two solid metal frames, which hold nine fused quartz pieces of various shapes (Figure 4.3). Both the inner and outer frames are equipped with water cooling channels. The window must sustain high pressures as well as high temperatures.

To detect the operational limits of this novel window, a comprehensive thermal evaluation was conducted by introducing air to the solar receiver/reactor. The experimental results confirmed good thermal performance, although the window transparency was slightly reduced over time by deposition of dust on the inside, in particular ceramic fibers from insulation materials and metallic particles from air pipes. It is assumed that these deposits were caused by improper operating conditions. During the tests, the receiver was opened twice to clean the window, since the contamination was favoring absorption of solar radiation and thus increasing the probability of re-crystallization of the quartz glass.

Final solar testing is scheduled for a period of two months in spring 2012. The goal throughout this test campaign will be to demonstrate the feasibility of the solar gasification process, to determine critical process parameters, and to identify possible problems in order to get a solid data base of the process. The experimental campaign will provide input to the pre-design of a 50 MW_{th} commercial plant in Venezuela.

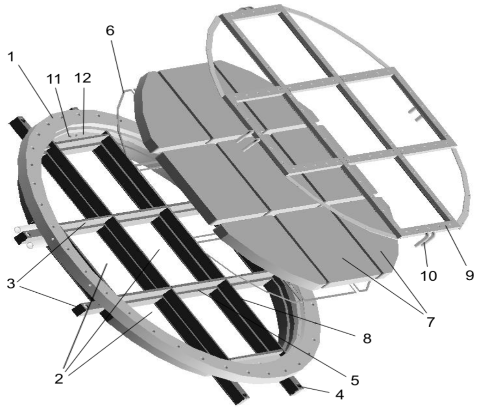

Figure 4.3. Components of the SYNPET-500 receiver/reactor window.

SOLSYN – Solar Process for High Quality Syngas from Low Grade Fossil Fuels and from Carbonaceous Wastes

Participants: PSI (CH), ETHZ (CH), Holcim (CH)

Contact: Christian Wieckert, christian.wieckert@psi.ch

Funding: Swiss federal funding agency (CTI) + Holcim (CH): € 1,300,000 (2nd phase)

Duration: Aug 1, 2009 – March 31, 2012 (2nd phase)

Background: In the first project phase (2007-2009), laboratory tests with a two-cavity batch solar reactor demonstrated the feasibility of solar steam gasification

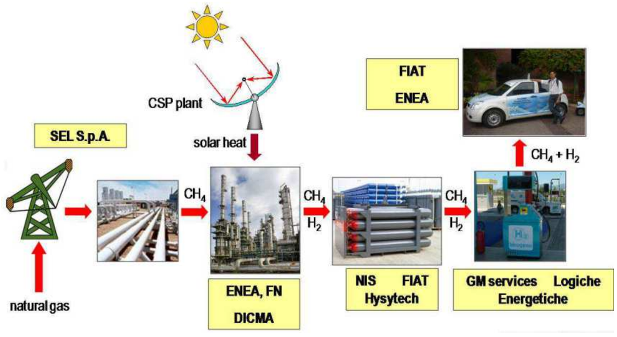

Figure 4.2. Conceptual scheme of the MET.I.SOL project.

for a wide range of carbonaceous feedstock [4.3]. Main process product is a synthesis gas (syngas, consisting mainly of H_2 and CO), which has a higher calorific value than the original feedstock material ("solar upgrade"). The syngas is intended to be used directly as fuel for firing cement kilns, as an alternative to using pulverized coal.

Purpose: The main project goal is to develop and operate an innovative pilot-scale solar reactor for steam gasification of coal, coke, and carbonaceous waste materials.

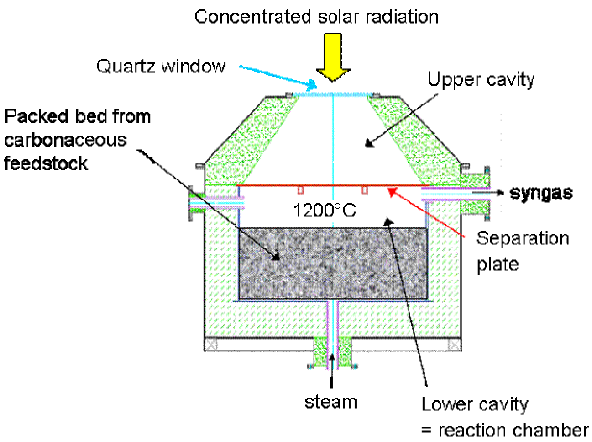

Figure 4.4. Scheme of solar steam gasification reactor for production of syngas from carbonaceous wastes.

Achievements in 2011: The 200 kW_{th} pilot plant – erected in 2010 at the Plataforma Solar de Almeria (PSA) – was successfully operated with nine different feedstocks including beech charcoal, low rank coal, tire chips, fluff, dried sewage and industrial sludge, and bagasse (cane trash). They were characterized by a wide range of volatile, ash, fixed carbon and moisture content, as well as elemental composition, particle size and morphology [4.4]. The batch packed-bed solar reactor technology (Figure 4.4) allows the direct use of wet and coarse materials – basically without any feedstock preparation (Figure 4.5).

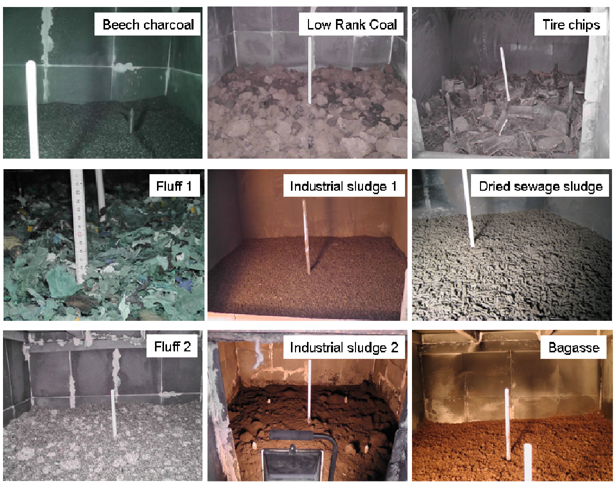

Figure 4.5. View of the pilot solar gasification reactor showing packed beds with different feedstocks prior to solar tests. The geometry of the reaction chamber floor is quadratic (1.1m x 1.1m).

The quality of the solar upgraded syngas produced from the various feedstocks was comparable. The transient operation of the 200 kW_{th} pilot-scale reactor for gasifying industrial sludge was simulated for a solar day, yielding a maximum solar-to-fuel energy conversion efficiency of 89% [4.5]. The findings of the pilot plant performance are used for the conceptual design of large-scale industrial solar steam gasification plants.

Publications: [4.3]-[4.5]

Solar Gasification of Biomass

Participant: UMN – University of Minnesota (USA)

Contact: Jane Davidson, jhd@me.umn.edu

Funding: UMN (USA): $1,000,000

Duration: July 2009 – August 2012

Background: Prior work has successfully demonstrated solar gasification, and this project builds on that work to reach higher efficiency through enhanced heat transfer, reduced formation of tar, and improved thermal stability.

Purpose: The primary objective is to develop and test a 5 kW_{th} solar receiver/reactor for gasification of plant biomass in a molten carbonate salt.

Achievements in 2011: Dramatic improvements have been demonstrated in the rate and total useful fuel production of steam gasification of a variety of feedstocks in a ternary eutectic blend of lithium, potassium, and sodium carbonate salts [4.6]. A prototype reactor has been designed and will be tested in the UMN high-flux solar simulator in 2012.

Publication: [4.6]

STCH – Solar Thermochemical Hydrogen

Participants: SNL – Sandia National Labs (USA), CU – University of Colorado (USA), ANL – Argonne National Lab (USA), SAIC – Science Applications International Corporation (USA)

Contact: Nathan Siegel, nps004@bucknell.edu

Funding: DOE – Department of Energy (USA)

Duration: Ongoing since 2004

Background: STCH began in 2004 with the goal of demonstrating commercially viable solar thermochemical hydrogen production cycles. Early efforts focused on cycle discovery and experimental validation followed by system level design and modeling. Reactor concepts, along with an appropriate solar interface, were identified for several classes of thermochemical cycles including metal oxide (volatile at CU and non-volatile at SNL), copper chloride (ANL), hybrid sulfur (SNL) and sulfur ammonia (SAIC). Economic analysis of several system concepts has been performed using the H2A program.

Purpose: The purpose of the STCH project is to demonstrate one or more commercially viable solar thermochemical hydrogen production systems. The project has technical as well as economic targets that include, among others, thermochemical cycle efficiency greater than 35% (solar input to the reactor to hydrogen, HHV) and a cost of hydrogen production of less than 3 USD/gge by 2017.

Achievements in 2011: SNL continued the development of a particle based reactor suitable for non-volatile metal oxide materials such as cerium oxide [4.7]. A system analysis of a dish-based version of this reactor shows that it can achieve an annual average solar to hydrogen production efficiency greater than 20% (Figure 4.6).

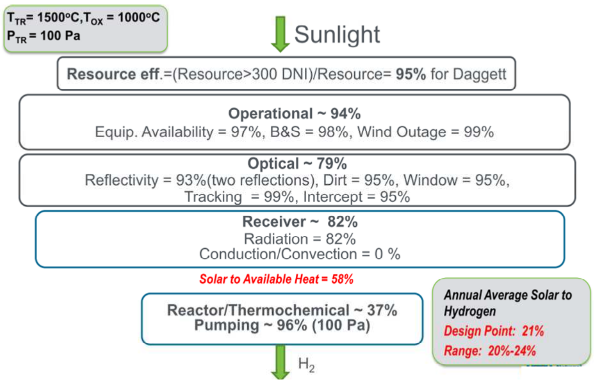

Figure 4.6. An energy walkthrough for SNL's particle reactor concept operating on a parabolic dish platform.

In addition, CU collaborated with SNL on the characterization of cerium oxide-based thermochemical cycles and led the development of a new cycle based on hercynite produced via atomic layer deposition (ALD) [4.8]. CU also continued the development of a gravity flow reactor suitable for metal oxide cycles using particulate reactants [4.9]. ANL continued to develop the hybrid copper chloride cycle with an emphasis on the electrolyzer component. They succeeded in experimentally demonstrating $CuCl_2$ electrolysis with hydrogen production using several different solid polymer membranes [4.10]. SAIC's work on the sulfur ammonia (SA) cycle involved several components including thermodynamic cycle analysis, experimental validation of key reactions, system level modeling, and economic assessment with H2A [4.11].

Publications: [4.7]-[4.11]

S2P – Sunshine to Petrol

Participant: SNL – Sandia National Labs (USA)

Contact: James E. Miller, jemille@sandia.gov

Funding: SNL (USA): Laboratory Directed Research and Development

Duration: 2008-2011

Background: The S2P project was the culmination of several years of solar thermochemical R&D at Sandia National Laboratories (SNL). While early efforts focused on hydrogen as an end product, the S2P project emphasized the thermochemical production of both carbon monoxide and hydrogen as a precursor to synthetic liquid transportation fuels. The S2P project included the following technical thrusts: reactor design and demonstration, materials development, and simulation and system level analysis [4.12].

Purpose: The goal of the S2P project was to establish a credible pathway to the large scale, commercially viable production of liquid transportation fuels from solar energy. This was done through a combination of analysis and technology development and demonstration embodied in the CR5 prototype thermochemical reactor.

Achievements in 2011: Significant progress was made in each of the three technical thrusts in 2011. With respect to materials, experiments were undertaken that elucidated and convincingly demonstrated the mechanism by

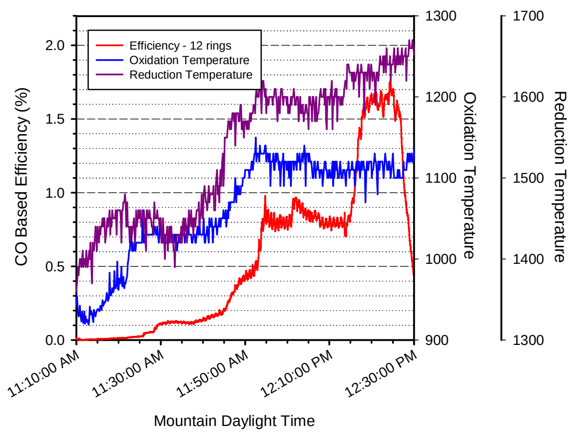

Figure 4.7. On-sun test data from the CR5 using twelve counter-rotating rings to produce CO from CO_2 in August of 2011.

which iron oxide is rendered cyclable by zirconia supports and the factors limiting the performance [4.13]. In addition, kinetic parameters for reduction and oxidation of ferrite and ceria materials were measured for use in reactor modeling. In the case of system level analysis, the primary economic drivers behind solar thermochemical fuel cost were identified as was a pathway toward ultimate viability for thermochemical fuel production technologies [4.14].

Finally, significant progress was made in the area of reactor development, culminating with the successful on-sun test of the CR5 with a measured efficiency of 1.7% as shown in Figure 4.7.

Publications: [4.12]-[4.14]

Solar Fuels via Metal Oxide Redox Cycles

Participants: UMN – University of Minnesota (USA), CALTECH (USA), UCLA (USA), ABENGOA SOLAR INC. (USA)

Contact: Jane Davidson, jhd@me.umn.edu; Wojciech Lipiński, lipinski@umn.edu

Funding: US NSF, US DOE ARPAE, UMN (USA): $7,000,000

Duration: July 2010 – June 31, 2014

Background: The UMN and its collaborating partners are developing materials and reactor technologies for rapid and efficient production of synthesis gas through utilization of ceria and zinc metal redox cycles. The focus is the ceria partial redox cycle.

Purpose: The primary objective is to reach a solar-to-fuel efficiency of 10% through advances in materials and highly effective heat recovery. Demonstrations of a 3 kW_{th} prototype ceria-based reactor in the UMN high flux simulator and on-sun at Abengoa's facility are planned for 2013/2014.

Achievements in 2011: UMN synthesized thin-walled, macroporous ceria structures, which have low tortuosity, high porosity, and high surface area. The structured ceria augments the rate of production of CO by nearly 300% [4.14]. Radiation characterization of ceria was completed for a range of porosities. Material compositions with improved stability are pursued at elevated temperature. A simplified approach has been developed for continuous solid phase heat recuperation that relies on radiative transfer of the porous reactive material to a counter rotating inert solid [4.16]. For the Zn/ZnO cycle, data show heterogeneous oxidation of Zn and rapid rates of oxidation for both H_2O- and CO_2-splitting of 1×10^{-5} mol cm^{-2} s^{-1} [4.17].

Publications: [4.14]-[4.17]

Solar Thermochemical H_2O/CO_2-Splitting via Volatile ZnO/Zn and SnO_2/SnO Cycles

Participant: CNRS-PROMES (F)

Contacts: S. Abanades, abanades@promes.cnrs.fr

Funding: CNRS (F), ANR (F)

Background: The production of solar fuels from H_2O and CO_2 via solar-driven two-step thermochemical cycles is investigated. The process involves a high temperature O_2-releasing dissociation reaction using concentrated solar energy followed by the exothermic H_2O/CO_2 splitting step. The research is focused on the ZnO/Zn and SnO_2/SnO thermochemical cycles. Each step of the cycles requires the detailed investigation of the chemical reaction systems. The implementation of such cycles requires the development of reliable solar reactors operating at high temperatures exceeding 1600°C.

Purpose: The goals of this study are: (1) determine the characteristics of the chemical steps and propose kinetic rate laws; (2) design and operate solar reactor prototypes and evaluate their performance for effecting the reduction reactions in a continuous mode; (3) simulate the reactor operation and evaluate the global energy efficiencies of the solar chemical processes.

Achievements in 2011: The exothermic oxidation of Zn and SnO with CO_2 to generate CO was investigated. Reactive Zn-rich and SnO-rich nanopowders were first synthesized in a high-temperature solar chemical reactor. This reactor was operated in controlled atmosphere at reduced pressure and reaction temperature of about 1600°C. The objective was to use realistic samples synthesized in a high-temperature solar reactor using concentrated solar power. Their reactivity was then investigated to demonstrate that the produced nanoparticles efficiently react with CO_2, which generates CO and the initial metal oxide that can be recycled [4.18].

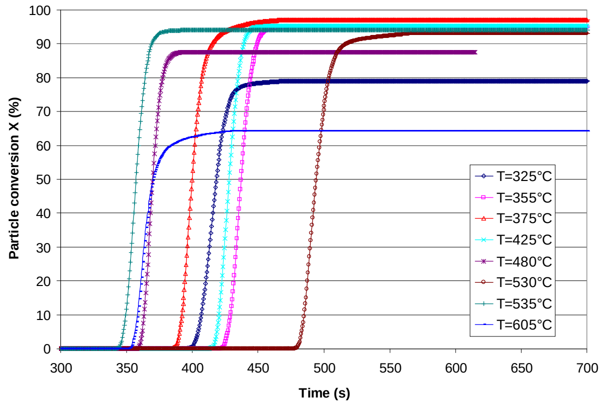

Figure 4.8. Influence of temperature during isothermal Zn powder oxidation in fixed bed for an inlet CO_2 mole fraction of 50%.

Thermodynamics predicts the formation of carbon at low temperatures and a narrow temperature range, in which CO formation is favored. However, experimental studies performed both in a thermogravimeter and in a fixed bed reactor demonstrate that the CO_2-splitting reaction is able to produce CO with high chemical conversion rates [4.19]. The results highlight that the synthesized powders are more reactive with CO_2 than standard commercial powders. The Zn can be oxidized by CO_2 with both high reaction rates and final chemical conversion over 90% above 360°C (Figure 4.8).

In contrast, the SnO oxidation requires both higher temperatures (around 800°C) and longer reaction duration to reach almost complete conversion. The reaction rates increased with the inlet CO_2 mole fraction, which is consistent with the power rate law. Experiments on CO_2-splitting were also performed in a fixed bed reactor that appeared suitable for efficient conversion of the solar-produced Zn metallic powders [4.20].

Publications: [4.18]-[4.20]

Solar Syngas Production from H_2O/CO_2 via Two-Step Zn/ZnO Thermochemical Cycle

Participant: ETHZ (CH)

Contacts: Aldo Steinfeld, aldo.steinfeld@ethz.ch

Funding: SFOE − Swiss Federal Office of Energy; SNSF – Swiss National Science Found.

Duration: January 1, 2010 – December 31, 2012

Background: Solar syngas production from CO_2 and H_2O is considered in a two-step thermochemical cycle via Zn/ZnO redox reactions, encompassing: (1) the ZnO thermolysis to Zn and O_2 using concentrated solar radiation as the source of process heat, and (2) Zn reacting with mixtures of H_2O and CO_2 yielding high-quality

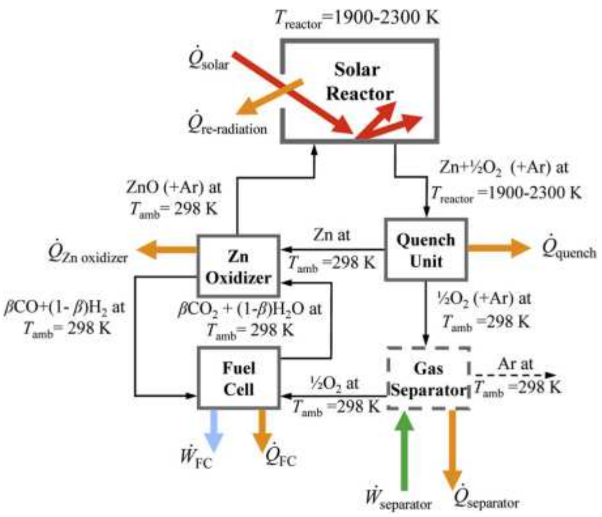

Figure 4.9. The model flow diagram of a two-step solar thermochemical cycle for splitting mixtures of CO_2 and H_2O simultaneously via Zn/ZnO redox reaction to produce syngas [4.21].

syngas (mainly H_2 and CO) and ZnO; the ZnO is recycled to the first, solar step, resulting in net reaction $\beta CO_2 + (1-\beta)H_2O \rightarrow \beta CO + (1-\beta)H_2$. Syngas is further processed to liquid fuels via Fischer-Tropsch or other catalytic reforming processes.

Purpose: The primary objective is to refine the science and develop the technologies to realize the second reaction step. A step-by-step methodology is being employed to evaluate the reaction potential with chemical thermodynamics, determine reaction mechanisms, and develop laboratory-scale reactor technologies.

Achievements in 2011: The potential of the two-step Zn/ZnO thermochemical cycle (Figure 4.9) was examined by second-law thermodynamic analysis [4.21]. At 1960°C and 1 bar, where $\Delta G = 0$, and for a desired syngas with a molar ratio H_2:CO equal to 2 – optimal for Fischer-Tropsch and methanol syntheses – the cycle efficiency reaches 31.5% when heat recuperation is not employed. At 1750°C, cycle efficiencies of up to 52.1% are attainable with a molar ratio of H_2:CO of 2 by recuperating the sensible and latent heat of the hot products exiting the solar reactor and the heat rejected by the reaction of Zn with H_2O/CO_2. Higher cycle efficiencies are also possible with higher fractions of CO_2 in the reactant gases. At below 1960°C, Ar dilution is required for complete ZnO-to-Zn conversion at 1 bar, which results in an energy penalty for the additional solar energy required for heating Ar without heat recuperation and additional work for separating O_2/Ar at the outlet of the quench unit.

A series of experimental runs of the second step was carried out in a packed-bed reactor where ZnO particles provided an effective inert support for preventing sintering and enabling simple and complete recycling to the first, solar step [4.21]. Experimentation was performed for Zn mass fractions in the range of 33–67 wt% Zn-ZnO and inlet gas concentrations in the range 0–75% H_2O-CO_2, yielding molar Zn-to-ZnO conversions up to 91%. A 25 wt% Zn-ZnO sample mixture produced from the solar thermolysis of ZnO was tested in the same reactor setup and exhibited high reactivity and conversions up to 96%.

Publications: [4.21]-[4.22]

Zn-Based Thermochemical Cycle for Splitting H_2O and CO_2

Participants: PSI (CH), ETHZ (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 – February 28, 2013

Background: A two-step solar thermochemical cycle for producing syngas from H_2O and CO_2 via Zn/ZnO redox reactions is considered [4.23]. The first, endothermic step is the thermolysis of ZnO to Zn and O_2 using concentrated solar radiation as the source of process heat. The second, non-solar, exothermic step is the reaction of Zn with mixtures of H_2O and CO_2 yielding high-quality syngas (mainly H_2 and CO) and ZnO; the latter is recycled to the first solar step, resulting in net reactions $CO_2 = CO + 0.5O_2$ and $H_2O = H_2 + 0.5O_2$.

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 kW_{th}) to pilot scale (solar power input of 100 kW_{th}). Experimental campaigns are scheduled at the 1 MW Solar Furnace (MWSF) in Odeillo, France.

Achievements in 2011: A 100 kW solar pilot plant for the thermal dissociation of ZnO to Zn and O_2 has been modeled, designed, and fabricated (Figure 4.10). To drive the dissociation reaction at about 1700°C, concentrated solar radiation is used as the energy source of high-temperature process heat. A first experimental campaign was conducted in 2011 at the 1 MW Solar Furnace (MWSF) in Odeillo, France [4.24]. 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 were tested and qualified. Valuable operational experience was gathered and, subsequently, helped to further improve the reactor design for the second experimental campaign planned for summer 2012.

Publication: [4.23]-[4.24]

Solar Thermochemical H_2O/CO_2-Splitting via Non-Volatile Ceria-Based Cycles

Participant: CNRS-PROMES (F)

Contacts: S. Abanades, abandes@promes.cnrs.fr

Funding: CNRS (F)

Background: The solar thermochemical splitting of CO_2 and H_2O with ceria and Zr-doped ceria for CO and H_2 production is considered. Zr-doped ceria is used to prevent sintering observed with pure ceria.

Purpose: $Zr_{0.25}Ce_{0.75}O_2$ was synthesized using different soft chemical synthesis routes to evaluate the influence of the powder morphology on the reactivity during the reduction and the oxidation steps. The reduction yield of ceria was significantly improved by doping with Zr as well as the CO/H_2 production yields, but the kinetic rates of the oxidation step for doped ceria were lower than for pure ceria.

Achievements in 2011: CO and H_2 production of 241 µmol/g and 432 µmol/g, respectively, has been measured. A kinetic analysis of the CO_2-splitting step allowed estimating the activation energy that ranged between 83 and 103 kJ/mol depending on the synthesis route of $Zr_{0.25}Ce_{0.75}O_2$ [4.25]. The powder morphology played an important role on the materials cyclability. In contrast to pure ceria, Zr-doped ceria showed possible deactivation when cycling at 1400°C and the influence of the synthesis route on the thermal stability was evidenced. The thermally resistant powders with porous morphology ensured stable reactivity during cycling. The Zr-doped ceria synthesized via Pechini process produced the largest amounts of CO/H_2 during successive cycles. Typical results for water splitting are shown in Figure 4.11.

Publication: [4.25]

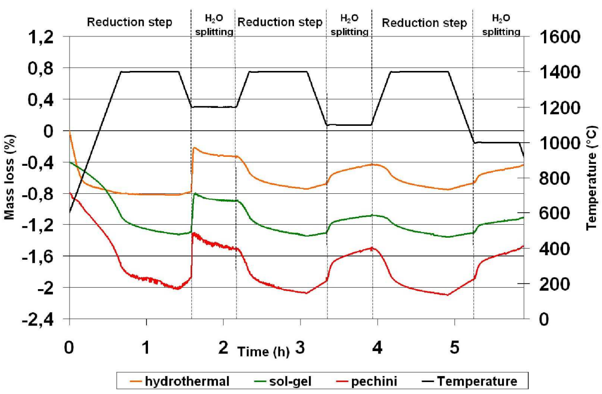

Figure 4.11. TGA of H_2O-splitting experiments during three successive cycles using $Ce_{0.75}Zr_{0.25}O_2$ [4.25].

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

Participants: Bauhaus Luftfahrt e.V. (D), ETHZ (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 CO_2 and H_2O to produce kerosene by coupling a two-step solar thermochemical cycle based on non-stoichiometric ceria redox reactions with the Fischer-Tropsch process [4.26], [4.27].

Purpose: The objective is to develop and optimize the solar reactor technology shown in Figure 4.12 for producing syngas by splitting H_2O and CO_2 via ceria-based redox cycles, and to further process the syngas to kero-

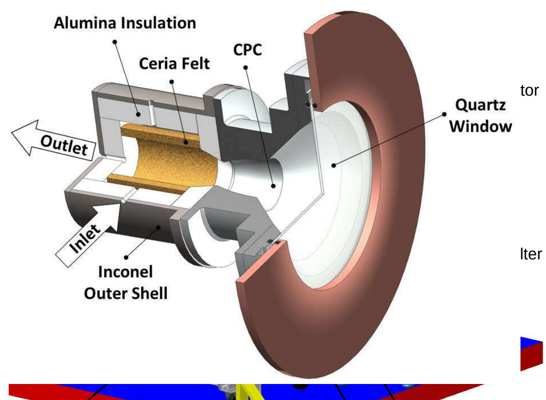

Figure 4.12. Schematic of the solar reactor configuration [4.28]. It consists of a cavity-receiver containing a porous ceria felt cylinder. Concentrated solar radiation enters through a windowed aperture and impinges on the ceria felt, while reacting gases flow radially across the porous ceria, and the product gases exit the cavity through an outlet port.

Figure 4.10. 3D rendering of 100 kW solar pilot plant [illegible] system [4.24].

sene. 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 2011: The work described here is conducted at ETHZ. Solar syngas production from H_2O and CO_2 was experimentally investigated using a two-step thermochemical cycle based on cerium oxide redox reactions in the solar reactor shown in Figure 4.12 [4.28]. The solar cavity-receiver, containing porous ceria felt, was directly exposed to concentrated thermal radiation at a mean solar concentration ratio of 2865 suns. In the first, endothermic step at 1530°C, ceria was thermally reduced to an oxygen deficient state. In the second, exothermic step at 830°C, syngas was produced by re-oxidizing ceria with a gas mixture of H_2O and CO_2. The syngas composition was experimentally determined as a function of the molar co-feeding ratio $H_2O:CO_2$ in the range of 0.8 to 7.7, yielding syngas with $H_2:CO$ molar ratios from 0.25 to 2.34. Figure 4.13 shows ten consecutive H_2O/CO_2-splitting cycles performed over an 8 hour solar experimental campaign.

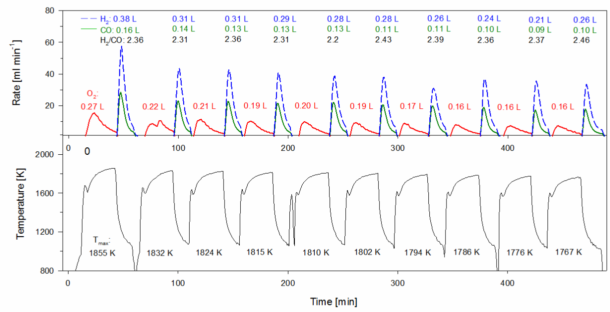

Figure 4.13. Temperature of the ceria felt, gas production rates, total amount of evolved gases, and H_2:CO molar ratios during ten consecutive splitting cycles. The reduction and oxidation steps were performed at constant time intervals of 30 and 15 minutes, respectively [4.28].

Publications: [4.26]-[4.28]

Solar Thermochemical CO_2 Capture

Participant: UMN – University of Minnesota (USA)

Contact: Wojciech Lipiński, lipinski@umn.edu

Funding: UMN (USA): $150,000

Duration: July 2011 – August, 2014

Background: This project seeks a major advancement of the solar thermochemical CO_2 capture technology via carbonation/calcination reaction pair. It provides a missing link between the development of sustainable cycles for renewable hydrocarbon fuel production from H_2O and CO_2, and anthropogenic CO_2 emissions.

Purpose: The objective is to develop a 3 kW_{th} solar reactor prototype and demonstrate CO_2 capture in the UMN high-flux solar simulator.

Achievements in 2011: Cycle thermodynamics have been extensively investigated and the potential in increasing the reactor efficiency due to solid and gas phase heat recovery has been identified. The reactor concept has been selected.

Publication: [4.29]

HYDROSOL-3D – Scale Up of Thermochemical H_2 Production in a Solar Monolithic Reactor: A 3rd Generation Design Study

Participants: CERTH/CPERI (GR), DLR (D), CIEMAT (E), Total Gas & Power SA (F), HyGear BV (NL)

Contacts: Martin Roeb, martin.roeb@dlr.de
Christian Sattler, christian.sattler@dlr.de

Funding: Hydrogen and Fuel Cell Joint Undertaking

Duration: January 1, 2010 – December 31, 2012

Background: HYDROSOL-3D aims at demonstrating CO_2-free H_2 production and related technology based on a solar-heated two-step water-splitting thermochemical process operating at moderate temperatures. It includes a support structure capable of achieving high temperatures when heated by concentrated solar radiation, combined with a redox system capable of water dissociation and at the same time suitable for regeneration at high temperatures. The process has been developed within the EU-FP5 project HYDROSOL and the EU-FP6 project HYDROSOL-2. After testing and validation of components and systems at prototype and pilot scales, the current focus is on the preparation of a 1 MW solar demonstration plant, which is the next step towards commercialization.

Purpose: The principal objective of HYDROSOL-3D is to (1) prepare an in-detail design of a 1 MW demonstration plant for thermochemical production of H_2 from H_2O using solar tower technology; (2) design and develop solar receiver/reactors with enhanced transport, thermal and heat recovery properties; (3) validate the operational reliability of plant design, control system, and components through laboratory and pilot plant testing; (4) decrease the temperature level of the regeneration step considerably below 1200°C; (5) design the solar field control system with commercial solutions available from the market.

Achievements in 2011: The design of the next generation reactor needs to be improved to significantly reduce thermal losses and to achieve a homogeneous temperature distribution within the honeycomb structure, while maintaining the modularity of the construction. To this end, a hemispherical absorber incorporating a secondary concentrator has been designed with optimized shape, geometry and dimensions (Figure 4.14). Further, various hydrogen purification options have been analyzed.

Experimental investigations with selected mixed iron oxide and rare-earth-based redox materials in powder form helped quantifying the effects of various operational parameters – such as water splitting/thermal reduction temperatures and steam mole fractions – on the hydrogen and oxygen yields [4.30]. Based on the experimental results, reaction rate models were formulated and kinetic parameters of water-splitting and thermal decomposition reactions were extracted. Inconsistencies

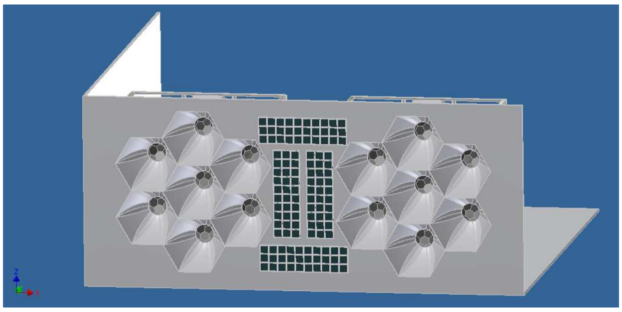

Figure 4.14. Scheme of the modular receiver/reactor set-up intended to be mounted on the solar tower platform.

in the reaction mechanism entail further refinement of the kinetic models to fully describe the two reactions throughout their duration.

In addition, honeycomb samples coated with active redox material have been tested in a solar reactor at DLR's high-flux solar simulator and – for comparison – in a laboratory set-up with an electrically heated tube furnace as the central element.

Parallel work involved the implementation of control strategies and algorithms for the pre-design of the process control system. The operational strategy was fine-tuned, in particular concerning the timing of the process steps involved. Experimental series have been carried out with the 100 kW_{th} pilot plant at the SSPS tower of the Plataforma Solar de Almería (PSA) to optimize the half-cycle duration, as well as the mass flows and the composition of feed streams. Recommendations for the operational strategy have been elaborated.

Publication: [4.30]

HycycleS – Solar Production of Hydrogen by the Sulfur-Iodine and Westinghouse Thermochemical Cycles

Participants: DLR (D), CEA (F), University of Sheffield (UK), CERTH/CPERI (GR), JRC (NL), ENEA (I), ETHZ (CH), Empresarios Agrupados (E), BOOSTEC (F)

Contact: Martin Roeb, martin.roeb@dlr.de

Funding: EC (FP7), DLR (D)

Duration: January 1, 2008 - March 31, 2011

Background: Solar thermochemical processes offer the potential of highly efficient massive hydrogen production at competitive costs. Worldwide, high priority is currently given to sulfur-based cycles, i.e. the sulfur-iodine (SI) and the hybrid sulfur (HyS) cycle, because they can be operated at temperatures making possible the use of concentrated solar radiation as the source of process heat. However, high temperatures and corrosive environments in their key steps present major challenges. The severe operating conditions require advanced materials as well as special design and fabrication methods. The key components common to both cycles include the oxygen separator, the H_2SO_4 evaporator and the SO_3 decomposer. The latter has to withstand the highest temperature in the cycles exceeding 850°C and is one of the main foci of the EC-funded project HycycleS.

Purpose: Develop and improve materials and key components for sulfuric acid decomposition: (1) recommend suitable materials and catalyst/support systems needed for key components of H_2SO_4 decomposition; (2) construct and test a solar receiver/reactor for H_2SO_4 evaporation/decomposition ready for scale-up; (3) realize and verify the feasibility of a compact SiC plate heat exchanger as H_2SO_4 decomposer; (4) acquire detailed understanding of transport properties and reaction performance of porous ceramic structures as reaction containment for the solar decomposition of H_2SO_4; (5) develop stable and reliable membranes for use in a separation step to significantly increase the conversion of SO_3 to SO_2.

Achievements in 2011: Candidate catalyst materials for the high temperature reduction of SO_3 have been screened and analyzed – mainly focusing on oxides of transition metals. Their catalytic activity, durability, and stability was experimentally investigated and quantified. Based on these systematic studies and on the ex-situ post-characterization activities, a Cr-Fe mixed oxide was found to be among the most promising catalytic materials examined.

Using suitable construction and catalyst materials, several prototype SO_3 decomposers have been developed and experimentally investigated. A large-scale heat exchanger/reactor prototype composed of SiC plates has been fabricated and successfully tested, showing prom-

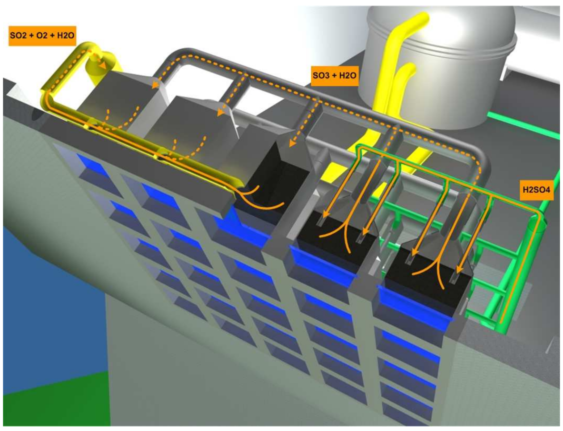

Figure 4.15. Modular arrangement of the receiver/reactor for sulfuric acid decomposition and piping on top of a solar tower.

ise with respect to its use for H_2SO_4 decomposition in both the SI and HyS cycles – either solar or nuclear [4.31].

A specific solar decomposer prototype has been developed, modeled, realized and tested on sun in a solar furnace at DLR Cologne. The two-chamber reactor consists of volumetric absorbers that directly couple concentrated solar radiation into the process, allowing to perform both evaporation of liquid H_2SO_4 and subsequent catalytic decomposition of SO_3.

A specific demonstration scenario has been depicted and analyzed; it foresees a multiple of individual receiver modules in an area-wide arrangement and the integration of all necessary components of a HyS chemical hydrogen production plant in a dedicated solar tower system (Figure 4.15) [4.32].

Publications: [4.31]-[4.32]

CENIT-CONSOLI+DA – Industrial Consortium of Solar Research and Development

Participants: Hynergreen Technologies S.A. (E), IMDEA Energía (E), CIEMAT (E), CIDAUT (E), Universidad Rey Juan Carlos (E)

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Alberto Quejido, alberto.quejido@ciemat.es

Funding: Spanish Ministry of Science and Education (CENIT): € 300,000

Duration: January 1, 2009 - December 31, 2011

Background: The CONSOLI+DA project is an ambitious initiative that involves an industrial consortium of twenty solar R&D institutions including reputed Spanish companies and most prestigious technological centers. Within the activity "Solar Hydrogen", the program of work aims to investigate the incorporation of high-temperature thermochemical cycles for the production of H_2 into solar concentrating technologies. The work combines state-of-the-art technologies and fundamental research for the development of cycles with high technical and economic potential.

Purpose: Two-step water splitting processes, such as ferrite cycles, are considered attractive candidates for solar hydrogen production, since there is no phase transformation during the redox cycle. The objective is to evaluate commercial and synthetic ferrites substituted with various metals for producing H_2 from H_2O through two-step thermochemical cycles.

Achievements in 2011: An experimental study has been performed in order to evaluate the activity of commercial and synthetic ferrites substituted with different metals (Ni, Cu, Zn, Co, and Mn) and to assess their viability for H_2 production from H_2O through two-step thermochemical cycles. Among all the samples studied, synthetic $CoFe_2O_4$ and commercial $NiFe_2O_4$ appear as the most promising materials for H_2 production, being able to generate up to 42.7 N·cm^3/g and 31.0 N·cm^3/g, respectively, after two thermochemical cycles (Figure 4.16). $CoFe_2O_4$ produces a larger amount of H_2 per cycle than $NiFe_2O_4$, but the H_2 production rate slightly

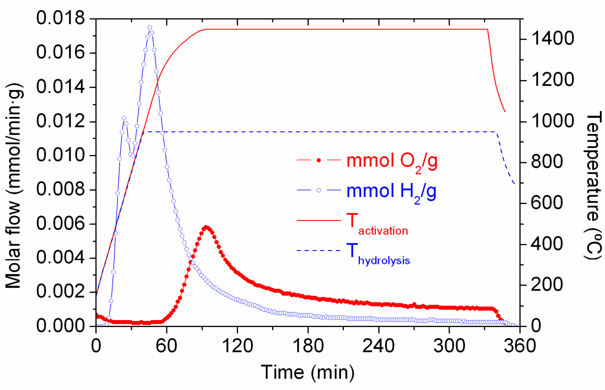

Figure 4.16. Activation and hydrolysis profiles (molar flow vs. time), and reaction temperatures of the first thermochemical cycle with the synthetic cobalt ferrite ($CoFe_2O_4$).

drops with increasing number of cycles. In contrast, for both commercial and synthetic Ni ferrites the H_2 production rate increases with the number of cycles.

INNPACTO-SolH2 – Innovative Technologies for Hydrogen Production

Participants: Hynergreen Technologies S.A. (E), IMDEA Energía (E), CIEMAT (E), Universidad de Sevilla (E)

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

Duration: June 1, 2011 - June 31, 2014

Background: Thermochemical cycles are expected to produce large amounts of H_2 in a cost and energy efficient way. Attractive candidates are two-step water splitting processes – e.g., based on ferrites – since there is no phase transformation during the redox cycle. Previous work performed within the CENIT-CONSOLI+DA project has been focusing on the evaluation of commercially available ferrites of different compositions. Among the samples studied, $NiFe_2O_4$ appeared as the most active materials regarding both net H_2 production and cyclability; at this stage, it was selected as the first candidate for solar experiments.

Purpose: The INNPACTO project aims at designing, constructing, and testing an innovative 100 kW$_{th}$ solar reactor prototype to be mounted on a solar tower and operated at temperatures between 1100-1300ºC.

Achievements in 2011: In the first phase of the project, the engineering design of the scaled-up reactor was advanced and further insight was gained in the heat transfer processes affecting the reactor's performance.

CIEMAT is preparing the solar flux maps from numerical simulations based on the direct normal irradiance (DNI) and the actual heliostat field configuration. IMDEA and Universidad de Seville are defining the boundary conditions for the computational fluid dynamics (CFD) simulations of the reactor in order to determine the temperature distribution and the maximum heat fluxes.

In 2012, construction of the 100 kW_{th} reactor and its operation on the SSPS-tower at the Plataforma Solar de Almería (PSA) is foreseen.

HYDROGEN-E PLAN − Research Infrastructure Support for Improving CRS-SSPS Facilities for Solar Thermochemical Hydrogen Production Activities

Participant: CIEMAT (E)

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Funding: Spanish Program for International Scientific Cooperation (FCCI): € 550,000

Duration: January 1, 2010 – March 31, 2013

Background: The current economic situation in Spain has led the Government to launch a series of extraordinary measures to give impetus to economic activity and employment. One is the Special Fund for the Revitalization of the Economy and Employment (E Plan). This plan is directed to carry out actions in the context of strategic productive areas, such as the hydrogen and fuel cell sector. As a major R&D installation in the energy sector, the Plataforma Solar de Almería (PSA) has been included in this initiative to boost the share of renewable energies.

Purpose: The project budget is addressed to accomplish major technology investments at the CRS-SSPS solar tower test facility, with the intention to offer unique research services to users from various countries (Figure 4.17).

Achievements in 2011: The CRS-SSPS solar plant consists of a heliostat field of 91 Martin-Marietta units and a 43 m high tower. At present, the solar tower accommodates two important projects for solar thermochemical H_2 and syngas production: (1) the 100 kW_{th} receiver/reactor of the HYDROSOL-II project on the first platform (32 m high); (2) the 500 kW_{th} receiver/reactor of the SYNPET project on the second platform at the top (43 m high).

The refurbishment of the SSPS-CRS tower includes the reinforcement of the metallic tower structure and the installation of a third platform to extend the capability to accommodate more solar experiments at the same time.

Figure 4.17. Side view of the CRS-SSPS plant at PSA, Spain, showing the two existing experimental platforms at 32 m and 43 m height, respectively.

Further investments have been provided for new equipment such as crane, heat exchanger, cooling tower, nitrogen and air supply, optical fibers for communication, etc.

Ammonia Thermochemical Storage

Participant: ANU – Australian National University (AUS)

Contacts: Greg Burgess, Greg.Burgess@anu.edu.au
Rebecca Dunn, Rebecca.Dunn@anu.edu.au

Background: Thermochemical energy storage based on ammonia is one of a number of storage options for concentrating solar power, including molten-salt storage, which is already operating commercially. The ammonia storage development has involved prototype solar receiver/reactors operated in conjunction with a 20-m^2 dish concentrator, as well as closed-loop storage demonstrations. The ammonia storage system could employ industry-standard ammonia synthesis converters for superheated steam production. A standard 1500 t/day ammonia synthesis reactor would suffice for a 10-MW_e base load plant with 330 large 489-m^2 dishes. At this stage, an updated economic assessment of the system would be valuable [4.33].

Purpose: The aim of current research is to improve ammonia conversion efficiencies with dish concentrators by optimizing the receiver geometry based on a frustum of reactor tubes (Figure 4.18).

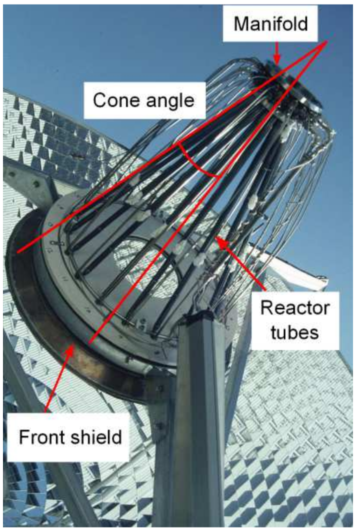

Figure 4.18. The prototype solar ammonia receiver/reactor for the 9 m^2 dish with a 17.5^o half cone angle (insulation removed).

Achievements in 2011: Achievements include an experimental program with a 9 m^2 dish which demonstrated a 7% increase in solar-to-chemical conversion efficiency with different receiver cone angles [4.34].

Publications: [4.33]-[4.34]

4.2.2 SOLAR PROCESSING OF CHEMICAL COMMODITIES

ENEXAL – Novel Technologies for Energy and Exergy Efficiency in Primary Aluminum Production Industry

Participants: ALUMINIUM S.A. (GR), NTUA (GR), RWTH (D), ETHZ (CH), WIS (IL), TMF Belgrade (Serbia), SIRMIUM Steel (Serbia), D'Appolonia S.p.A. (I), Pegaso Systems s.r.l. (I), Lindbergh Trading (Pty) Ltd. (RSA)

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Funding: EC funded project, cost shared: € 4,950,000

Duration: June 1, 2010 - May 31, 2014

Background: Primary aluminum production industry is the world's largest industrial consumer of energy and ranked among the most CO_2 intensive industries. It also generates enormous quantities of wastes that further decrease the exergy efficiency of its production process. However, this industry is one of the most vital sectors from the economics and social points of view, not only for the EU but also for the entire world. In order to remain viable and competitive, a primary aluminum industry has to operate in a smarter way, be more energy efficient and meet environmental requirements of our times. This can be achieved only through radical new technologies and novel business strategies, which will enable the industry to maintain its competitiveness, fasten its viability in the world's markets and explore new business opportunities.

Purpose: The main goal of this project is to provide primary aluminum industry with "green" innovative technological and economical solutions, focusing on (1) significant improvement of energy and exergy efficiencies of the production process; (2) substantial reduction of GHG emissions; and (3) complete elimination of the solid wastes ("red mud").

Achievements in 2011: In order to achieve these objectives, novel technologies for the reduction of alumina to aluminum and complete utilization of the red mud will be demonstrated and validated on pilot scale. These technologies are energy-efficient and environmentally acceptable, ensuring the competitiveness of the industry. The technologies under development are: 1) high temperature carboreduction of alumina in an electric arc furnace (EAF) and 2) carboreduction of alumina in a vacuum solar reactor, 3) full utilization of the red mud in a novel electric arc furnace suitable for processing dusty materials without pre-treatment [4.35]. Under reductive smelting process, where carbon is used as reducing agent, red mud is totally converted into valuable pig iron for steel production and glassy fibers for mineral wool production.

In 2011, conversion of the red mud was demonstrated on a 400 KVA scale at NTUA, Greece. A larger 1 MVA pilot furnace is under construction at ALUMINUM Greece.

The basic laboratory studies for the reduction of alumina under vacuum, which include thermodynamics and kinetics analyses, back reactions and possible side products (carbides and oxy-carbides) have been conducted using induction furnaces both at ETHZ and WIS [4.36], [4.37]. Based on the results of these experiments, a 30 kW_{th} solar reactor was designed.

Publications: [4.35]-[4.35]

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[4.36] Halman M., Epstein M., Steinfeld A. (2012) Vacuum carbothermic reduction of Bauxite components: A thermodynamic study. *Mineral Processing and Extractive Metallurgy Review* 33(3), 190-203.

[4.37] Halman M., Epstein M., Steinfeld A. (2011) Carbothermic reduction of alumina by natural gas to aluminum and syngas: A thermodynamic study. *Mineral Processing and Extractive Metallurgy Review*, GMPR-2011-0021, in press. DOI**:** 10.1080/08827508.2011.601482.

5. Task III: Solar Technology and Advanced Applications

Operating Agent: Peter Heller, DLR

5.1 Nature of Work & Objectives

The objectives of this task deal with the advancement of technical and economic viability of emerging solar thermal technologies and their validation with suitable tools by proper theoretical analyses and simulation codes as well as by experiments in special arrangements and adapted facilities. For this purpose, procedures and techniques are defined for the design, evaluation and use of the components and subsystems to optimize concentration, reception, transfer, storage and application of solar thermal energy. In essence, the goals are to investigate innovative multi-discipline advances needed for the further development of concentrating solar thermal systems.

Task III is an ongoing R&D-oriented effort with clearly defined technical objectives, time schedule and expected results. Activities are cost-shared, task-shared (either through SolarPACES or among SolarPACES participants), and/or information-shared. Cost-sharing and task-sharing activities involve cooperative efforts of two or more participants where either costs of activities or responsibilities for activities, respectively, are mutually agreed upon and shared by the Participants. Information sharing is used for the exchange and discussion of results of projects carried out independently by Participants, but of interest to all.

5.2 Reported Task III activities in 2011

Reported Task III Activities in 2011 are summarized in Table 5.1. The different ways of cost- and/or task sharing are marked in the last column:

1. Cost-shared activities created and coordinated through SolarPACES (C in Table 5.1)
2. Task-shared activities created and coordinated through SolarPACES (T in Table 5.1)
3. Task-shared activities created and coordinated by SolarPACES member countries (eventually with participation of non-member countries) which are of interest to SolarPACES (M in Table 5.1)
4. Activities of individual member countries, which are of interest to SolarPACES (I in Table 5.1).

5.3 Task III Objectives 2012-2016

The main important objectives for the Task III activities in the upcoming period of the IEA SolarPACES Strategic Plan reaching from 2012 to 2016 will be to achieve a further significant cost reduction for new plants and to guarantee a high performance over the life time of the plant. Cost reduction may be reached through simplifications, mass production or evolution in manufacturing processes but additionally through new developments of advanced materials, processes and concepts. A further increase of operation temperatures will have major impact on cost reductions. The strong emphasis on the following topics is therefore planned for the next period:

1. Prioritization of R&D activities with high impact on cost reduction
   - Components for direct steam generation
   - Novel concepts for tower systems at increased temperatures
   - Advanced materials for high-temperature absorbers and reactors
   - Fluids for increased temperatures (salt mixtures, synthetic oils, liquid metals, gases, etc.)
   - Heliostat control and field maintenance to achieve high concentration ratios in large scale
   - Development of new coatings for improved performance at higher temperatures

2. Reliability Evaluation of solar components and systems
   - Methods to evaluate components reliability on laboratory scale and in the field
   - Development of instruments for characterization

3. Methods for durability and life time predictions
   - Improved instruments to measure degradation
   - Expansion of laboratory test equipment for broad materials classification and comparison
   - Development of models for life time prediction for different materials
   - Round robin tests for comparison of results
   - Proposal for standards on durability testing and life time prediction CO_2, can produce a range of solar-enriched fuels and synthesis gas (mainly H_2 and CO) that can be used as a chemical feed stock or a metallurgical reducing gas.

4. Tools and methods for quality assurance of concentrator systems
   - Development of commercial tools for quality assurance of different concentrator types

- Provision of calibration standards for instruments
- Concepts for improved methods and implementation in advanced instruments

5. Guidelines for component performance measurements
- Development of guidelines for measurement of shape, receiver performance, accelerated ageing methods, etc.
- New instruments capable to measure according new standards
- Calibration standards and round robin tests for verification of precision

6. Component performance in desert environment (soiling, extinction, cleaning)
- Analysis of typology of different desert environments concerning soiling and weather characteristics
- Measurement of extinction in different desert zones and implementation in models for tower plants simulations.
- New instruments to monitor soiling and extinction
- Development of cleaning procedures with low water consumption

Table 5.1. Summarized Task III reported activities organized by sector

	Concentrating Solar Technology and Applications	Contact	Sharing			
	Components and Subsystems		**I**	**M**	**T**	**C**
Trough	An air based Cavity Receiver for Solar Trough Concentrators	Aldo Steinfeld	x			
Trough	Development of a large aperture cost-optimized parabolic trough using mirror film	Alison Mason	x			
Trough	Field testing of high reflectance, outdoor mirror film and addition of abrasion resistant coating	Alison Mason	x			
Trough	GEMASOLAR, VALLE 1 & VALLE 2 PLANTS	Torresol (Oihana Casas Marin)				
Tower	GEMASOLAR TECHNOLOGY	Sener (Oihana Casas Marin)				
Tower	A Pressurized Air Receiver for Solar-driven Gas Turbines	Aldo Steinfeld	x			
Dish	Development and installation of the HelioFocus large Dish/Booster prototype	Thomas Keck	x			
Storage	High Temperature Thermal Storage using a Packed Bed of Rocks	Aldo Steinfeld	x			
Storage	Optimization of thermal storage components and equipment	Esther Rojas	x			
	Supporting Tools and Test Facilities					
	OPAC Optical Aging Characterization Laboratory	Stephanie Meyen	x			
	SFERA: Solar Facilities for the European Research Area	Diego Martinez	x	x		
	Standards for CSP components					
	Development of guidelines for standards for CSP components	Peter Heller	x		x	x
	Guideline for standard for reflector shape analysis	Eckhard Luepfert	x		x	x

5.4 Summary of Achivements in 2011

An Air-Based Cavity-Receiver for Solar Trough Concentrators

I = individual member country activities of interest to SolarPACES	X
M = member country task-shared activities of interest to SolarPACES	
T = SolarPACES task-shared activities	
C = SolarPACES cost-shared activities	

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Website:
http://www.pre.ethz.ch/research/projects/?id=airlight

Funding: Swiss Federal Office of Energy

We have built and tested a novel tubular cavity-receiver concept for solar trough concentrators which employs air as the heat transfer fluid (HTF) [1]. The advantages are four-fold: 1) operating temperature constraints due to chemical instability of the HTF are avoided; 2) operating pressure can be close to ambient, eliminating the need for sophisticated sealing; 3) a packed-bed thermal storage can be heated directly by air, eliminating the need for a heat exchanger between HTF and thermal storage medium; and 4) costs for the HTF are removed. The disadvantages of air-receivers are associated with the larger volume flow rate and surface area needed due to the lower volumetric heat capacity and convective heat transfer of air as compared to liquid HTFs (e.g. thermo-oils, molten salts, sodium).

A 42m-long full-scale solar receiver prototype was tested on a 43.5m-long 9m-aperture full-scale parabolic trough concentrator, consisting of pneumatically spanned multilayer polymer mirror membranes installed on a 1-axis tracking concrete frame. [2]. A cross-section of the solar receiver prototype is shown in **Fig. 1**, the test facility is shown **Fig. 2**. A heat transfer model was developed and experimentally validated in terms of simulated and measured HTF and receiver temperatures, and HTF pressure drops. The efficiency of the prototype receiver, predicted with the validated heat transfer model, is shown in **Fig. 3** for constant receiver inlet temperature of 120°C and varying outlet temperature.

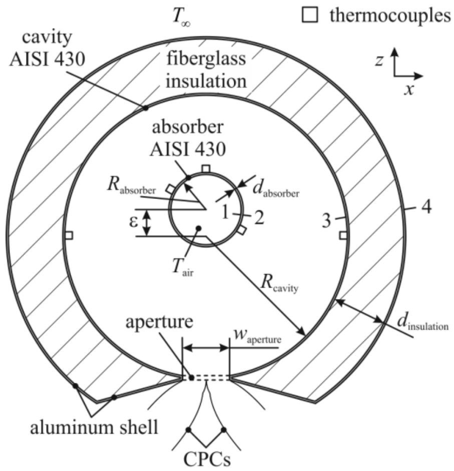

Fig. 1: Cross-section of the cavity receiver prototype.

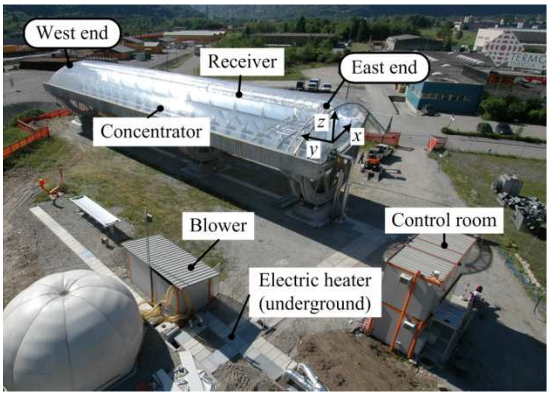

Fig. 2: Receiver test facility in Biasca, Switzerland.

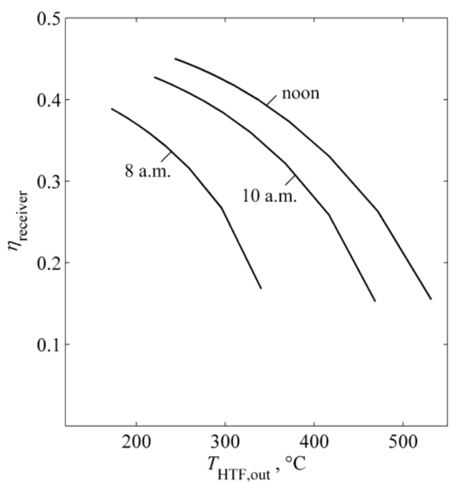

Fig. 3: Numerically calculated efficiency of the 42-m-long prototype receiver, as a function of the outlet temperature; inlet temperature: 120°C; date: summer solstice, 8, 10, 12 a.m. solar time.

References:

[1] Bader R., Pedretti A., Steinfeld A., "Experimental and Numerical Heat Transfer Analysis of an Air-Based Cavity-Receiver for Solar Trough Concentrators", *ASME Journal of Solar Energy Engineering*, Vol. 134, pp. 021002-1/8, 2012.

[2] Bader R., Pedretti A., Steinfeld A., "A 9m-Aperture Solar Parabolic Trough Concentrator Based on a Multilayer Polymer Membrane Mounted on a Concrete Structure", *ASME Journal of Solar Energy Engineering*, Vol. 133, 031016-1/12, 2011.

Development of a large aperture cost-optimized parabolic trough using mirror film

I = individual member country activities of interest to SolarPACES	X
M = member country task-shared activities of interest to SolarPACES	
T = SolarPACES task-shared activities	
C = SolarPACES cost-shared activities	

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Participants: SkyFuel

Funding: appr. $4.3M from US Department of Energy

High-reflectance mirror film has been proposed as a pathway to significant reduction in the Levelized Cost of Energy (LCOE) of parabolic trough solar concentrators. Use of mirror film in place of glass mirror facets allows for larger, continuous trough apertures and more accurate optics, which in turn permit higher concentration ratio, higher temperature operation, and lower cost of components per unit aperture.

This project was funded by the United States Department of Energy to develop a parabolic trough collector that enables solar electricity generation in the 2020 market place for a 216MWe nameplate baseload power plant with an LCOE of 9¢/kWhe, a capacity factor of 75%, a limit of 15% fossil fuel fraction, a fossil fuel cost of $6.75/MMBtu, $25.00/kWht thermal storage, and a USA installation corresponding to Daggett, CA.

SkyFuel examined the design of almost every parabolic trough component from a perspective of load and performance at aperture areas from 500 to 2900m^2. We combined aperture dependent design with fixed quotations for like parts from our baseline SkyFuel product.

Our major optimization effort was devoted to increasing aperture to reduce cost, accounting for the impact of aperture on performance, and selecting an optimum based on LCOE. We used the NREL System Advisor Model to combine the disparate cost and performance terms, and estimate the LCOE. For inputs that affect LCOE but were outside the scope of our work, we used the standard DOE template values.

The result of our optimization was a trough design of larger aperture and operating temperature than has been fielded in large, utility scale parabolic trough applications, specifically 8m width x 150m SCA length (1176m^2 aperture), with four 80mm diameter × 4.7m receivers per mirror module and an operating temperature of 500°C.

Field testing of high reflectance, outdoor mirror film and addition of abrasion resistant coating

I = individual member country activities of interest to SolarPACES	X
M = member country task-shared activities of interest to SolarPACES	
T = SolarPACES task-shared activities	
C = SolarPACES cost-shared activities	

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Participants: ReflecTech, Inc.

Funding: US Department of Energy, Technology Commercialization Deployment Fund

Durable highly reflective polymer film is a design innovation that makes possible significant reductions in lifecycle costs of solar concentrators by providing larger and lighter alternatives to typical curved glass mirrors. The development and commercialization of ReflecTech mirror film has been documented in DiGrazia et al 2009 (ASME), DiGrazia et al 2010 (ASES), and DiGrazia et al 2011 (ASME).

In SkyFuel's parabolic trough (SkyTrough), ReflecTech mirror film is laminated to an aluminum sheet substrate to form a monolithic mirror panel. The panels slide into place, span the entire aperture width, and are used in place of traditional glass mirror technology. A 1 MWth loop of SkyTrough collectors was installed in an operating solar power plant (SEGSII) in December, 2009 and individual panels are visible in Figure 1.

The mirror panel reflectance has a direct impact on trough performance; consequently, it is measured with a repeatable sampling method on a regular basis at the SEGSII facility. These reflectance measurements are taken with a Devices and Services specular reflectometer at a single wavelength (660 nm), with a 25 milliradian instrument aperture. All measurements are taken at the same four points of each mirror module: 600mm from the east and west rim and 600mm from the north and south edge of exterior panels. A data set includes 72 measurements which are averaged to provide a single indication of reflectance. The standard deviation of the measurement set is typically ranges from 0.3 to 0.5 reflectance points. Measurements are always taken on the collector immediately following a high pressure wash of the collectors, executed on a regular pattern by the power plant operators.

The clean reflectance of the SkyTrough is shown in Figure 2. The average reflectance is 93.4%. The reflectance of SkyTrough mirror panels at the SEGSII commercial plant has been maintained, without loss, within the uncertainty of the measurement data sets.

The development and testing of an abrasion resistant coating (ARC) for ReflecTech mirror film was documented by Jorgensen et al in 2010 (SolarPACES). 52 ReflecTech mirror panels with the ARC were installed in the SEGSII loop in March, 2012 to begin long-term field demonstration of the commercially available ReflecTechPLUS.

Fig. 1: SkyTrough SCAs in operation at SEGSII in Daggett, California.

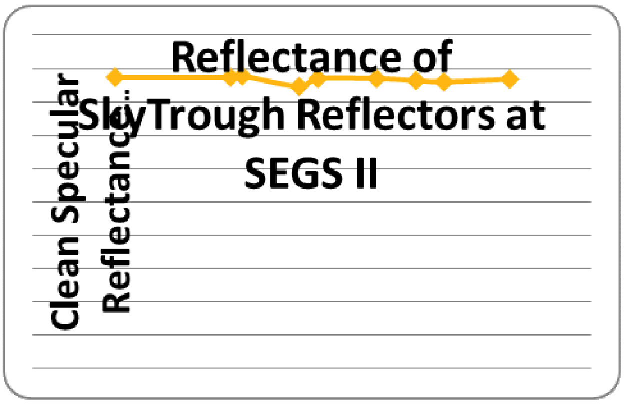

Fig. 2: Specular reflectance of ReflecTech mirror panels at SEGSII.

References:

M. DiGrazia, R. Gee, and G. Jorgensen, "ReflecTech® Mirror Film Attributes and Durability for CSP Applications", ASME Conference, Proceedings of Energy Sustainability 2009, July 19-23, 2009, San Francisco, California.

M. DiGrazia and G. Jorgensen, "ReflecTech® Mirror Film: Design Flexibility and Durability in Reflecting Solar Applications", ASES National Solar Conference 2010, American Solar Energy Society, May 17-22, 2010, Phoenix, AZ.

M. DiGrazia, G. Jorgensen, R. Gee, C. Bingham, and C. Loux, "ReflecTech□ Polymer Mirror Film Advancements in Technology and Durability Testing", ASME Conference, Proceedings of Energy Sustainability 2011, August 7-10, 2011, Washington, DC.

G. Jorgensen, R. Gee, and M. DiGrazia, "Development and Testing of Abrasion Resistant Hard Coats for Polymer Film Reflectors", SolarPACES 2010, September 21-24, 2010, Perpignan, France

Approximated method for modeling hemispherical reflectance and evaluating near-specular reflectance of CSP mirrors

I = individual member country activities of interest to SolarPACES	?
M = member country task-shared activities of interest to SolarPACES	
T = SolarPACES task-shared activities	?
C = SolarPACES cost-shared activities	

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Several commercial solutions alternative to conventional glass solar mirrors have been proposed; they are characterized by using a substrate other than glass, and being a "first surface mirror". Such new thin solar mirrors are offered as optical coatings or thin foils to be, respectively, deposited on or laminated to a rigid substrate which gives the desired shape to the facet. For economic reasons, the surface of that substrate (generally aluminum) cannot be polished to ensure high optical quality; therefore surface roughness causes light scattering phenomenon, large enough to appreciably spread the reflected solar beam when compared with those obtained by conventional glass solar mirrors.

On the other hand, in concentrating solar power (CSP) mirrors are just used to concentrate solar radiation on the receiver, and not for imaging the Sun: all the radiation reflected in the solid angle of receiver-viewing is useful. This makes a new mirror-evaluation methodology, which takes into account not only specular, but also near-specular reflectance, mandatory.

Unfortunately, light scattering depends on wavelength and incidence angle, and its exhaustive direct measurement is totally unpractical because it is time-consuming, experimentally complex, and costly.

At the Task III meeting held in Granada in September 2011, an approximated method to evaluate the effectiveness of these innovative solar mirrors was proposed. The method is based on two tools developed several years ago: the experimental set-up used for ITER mirrors characterization [1], and the equivalent model algorithm for the prediction of architectural-glazing angular-properties [2].

In brief, according to the method proposed here, the hemispherical reflectance ρ_h is measured at near-normal incidence with a commercial spectrophotometer equipped with an integrating sphere; the achieved spectrum is fitted with a proper equivalent model, allowing off-normal-incidence reflectance prediction for *s* and *p* polarization. The near-specular reflectance ρ_s is measured at three different wavelengths (red, green, blue) for a set of values of the apex angle φ covering the range of interest for the specific CSP application. Assuming the Total Integrated Scatter (TIS) relationship, the (equivalent) roughness associated to the investigated apex angle ϕ is given by,

$$\sigma_\varphi = \frac{\lambda_0}{4\pi}\sqrt{\ln\left(\frac{\rho_h(\lambda_0,0,h)}{\rho_s(\lambda_0,0,\varphi)}\right)}.$$

The agreement among the results achieved at the three different wavelengths indicates the correctness of the TIS assumption. Finally, the near-specular reflectance at off-normal-incidence is given by,

$$\rho_s(\lambda,\theta,\varphi)=\rho_h(\lambda,\theta,h)\ \exp\left[-\left(\frac{4\pi\sigma_\varphi\cos\theta}{\lambda}\right)^2\right].$$

The effectiveness of the solar mirror must be numerically evaluated by ray tracing for the specific CSP application, properly including the divergence of the solar radiation.

The method is currently under test. A public call was launched over the Task III email list, opening the collaboration with institutions, manufacturer and individuals.

References:

[1] G. Maddaluno, M. Di Fino, F. Orsitto, A. Rufoloni, M. Montecchi, E. Nichelatti, E. Serra, A. Litinovsky, G. Sergienko, G. De Temmerman, L. Marot, *Tests of rhodium-coated molybdenum first mirrors for ITER diagnostics*, 34th European Physical Society – Conference on Plasma mirrors -, Warsaw (Poland) July 2-6, 2007.

[2] M. Montecchi, E. Nichelatti, and P. Polato, *Hybrid equivalent model algorithm for the prediction of glazing angular properties*, Solar Energy and Solar Cells 71 (2002) 327-342.

A Pressurized Air Receiver for Solar-driven Gas Turbines

I = individual member country activities of interest to SolarPACES	**X**
M = member country task-shared activities of interest to SolarPACES	
T = SolarPACES task-shared activities	
C = SolarPACES cost-shared activities	

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Participants: ETH Zürich, ALSTOM

Website: http://www.pre.ethz.ch/research/projects/?id=solargasturbine

Funding: ALSTOM, EU-FP7 project SFERA.

In previous publications [1,2] we reported on a novel design of an air-based pressurized solar receiver for power generation via solar-driven gas turbines. A schematic of the solar receiver configuration is shown in **Fig. 1**. The main component of the indirectly-irradiated receiver concept is a cylindrical silicon carbide (SiC) cavity, surrounded by a concentric annular reticulate porous ceramic (RPC) foam. Absorbed heat is transferred by combined conduction, radiation, and convection to the pressurized gas flowing across the RPC. A 3 kW prototype was tested with air and He as working fluids at outlet temperatures up to 1335 K and a pressure of 5 bar [2]. The critical component is the ceramic cavity, which is exposed to concentrated solar radiation. The cavity-type geometry enables efficient capture of incident solar radiation through multiple internal reflections, approaching the behavior of a blackbody absorber. Absorbed radiation is transferred by conduction across the ceramic cavity walls, while withstanding high temperatures and pressures. Thus, the design constrains are mainly given by the limitations imposed by the materials of construction such as the maximum operating temperature, thermal conductivity, resistance to thermal shocks, and inertness to oxidation by air. Promising ceramic materials are reaction-bonded silicon infiltrated SiC (SiSiC) or pressureless sintered alpha SiC (SSiC), which allow maximum operating temperatures of about 1873 K at thermal conductivities in the range 30 - 125 $Wm^{-1}K^{-1}$ while offering stability against thermal shock, oxidation, and mechanical loads.

A set of four silicon carbide (SiC) cavity-receivers attached to a 3D compound parabolic concentrator were tested on a solar tower at stagnation conditions for 35 kW solar radiative power input under mean solar concentration ratios exceeding 2000 suns and nominal temperatures up to 1600 K. The experimental setup is schematically depicted in **Fig. 2**. A heat transfer model coupling radiation, conduction, and convection was formulated by Monte Carlo ray-tracing, finite volume and finite element techniques, and validated in terms of experimentally measured temperatures. The model is applied to elucidate the effect of material properties, geometry and reflective coatings on the cavity's thermal and structural performances. A pressurized air circuit was not integrated at this stage of the project. Input powers ranging from 32.5 to 37.4 kW were realized during the field campaign. A peak temperature of 1595 K was obtained and measured by means of infrared (IR) pyrometry for an incident solar flux of 2112 kW/m^2 at stagnation conditions [3]. Factors of safety for stress and temperature of the tested SiC materials were in the range of 2.0 - 4.2 and 1.0 - 1.5 respectively. 89% of the incident solar radiation can be conducted across the cavity wall and available as useful power, while re-radiation is the dominant source of heat loss.

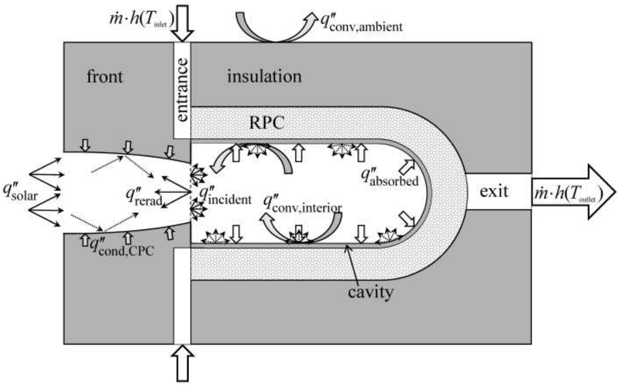

Fig. 1: Schematic of the solar receiver configuration consisting of a inner cylindrical cavity and a concentric annular RPC foam in a sealed pressurized vessel. Incoming concentrated solar radiation is efficiently absorbed by the cavity and transferred by conduction, radiation, and convection to the pressurized air flowing across the RPC [2].

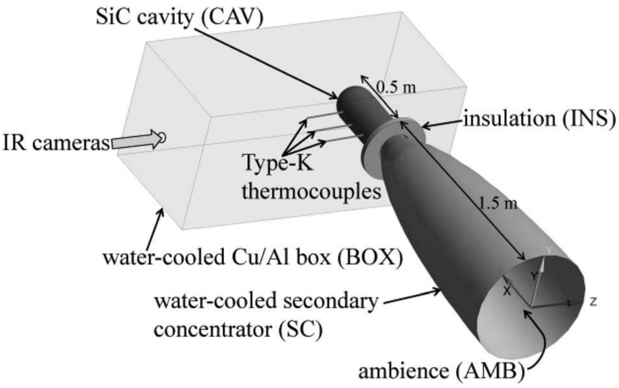

Fig. 2 – Schematic of experimental setup for testing ceramic cavity-receivers. It consists of cylindrical SiC cavity attached to a water-cooled secondary concentrator via an insulating ring and surrounded by a water-cooled box [3].

References:

[1] Hischier I., Hess D., Lipiński W., Modest M., Steinfeld A. Heat Transfer Analysis of a Novel Pressurized Air Receiver for Concentrated Solar Power via Combined Cycles. *ASME Journal of Thermal Science and Engineering Applications.* Dec., 2009, Vol. 1, pp. 041002

[2] Hischier I., Leumann P., Steinfeld A. Experimental and Numerical Analyses of a Pressurized Air Receiver for Solar-driven Gas Turbines. *ASME Journal of Solar Energy Engineering*, May., 2012, Vol. 134, pp. 021003

[3] Hischier I., Poživil P., Steinfeld A. A Modular Ceramic Cavity-Receiver for High-Temperature High-Concentration Solar Applications. *ASME Journal of Solar Energy Engineering*, Feb., 2012, Vol. 134, pp. 011004

Development and installation of the HelioFocus large Dish/Booster prototype

I = individual member country activities of interest to SolarPACES	X
M = member country task-shared activities of interest to SolarPACES	
T = SolarPACES task-shared activities	
C = SolarPACES cost-shared activities	

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Participants: sbp sonne gmbh (D), HelioFocus Ltd. (IL)

Funding: none

Background: HelioFocus of Ness Ziona, Israel, intend to market modular Dish/Booster systems. These shall provide high temperature steam to combined cycle or coal power plants. sbp was commissioned to develop a large-scale parabolic dish for this application. The conceptual design study had been carried out in 2008, the detailed design of the prototype started at the beginning of 2010.

Purpose: Demonstrate the technology, both the novel dish design and the receiver/heat transmission system. Provide a carrier for component testing and further development of the system.

Achievements in 2011: The detailed design was completed in early 2011. Manufacturing and site preparations were accomplished, site assembly commenced in September. By the end of 2011, the drive and control system commissioning was completed and the heat transfer system installation was underway.

The concentrator applies an unconventional design, based on a Fresnel arrangement of the 219 facets. This allowed to design a flat concentrator structure, consisting of a rigid torque box with 7 cantilever arms, and with dimensions of 26.5 x 25 m. The total reflective area is 493 m². The concentrator is carried by a turn table, made up of box sections and a counterweight. It runs on a circular crane rail with 18.5 m diameter. Large hydraulic cylinders are used for the elevation axis and an innovative hydraulic pilgrim step drive was applied for the azimuth rotation.

HelioFocus have developed and tested a volumetric air receiver in several precursory projects, which can reach air temperatures up to 1000°C. An isolated annulus piping solution with pivotable joints has been designed as well as the complete circuit for heat transfer and steam generation. This will be tested in 2012. HelioFocus intend to apply the technology for supplying stable steam under Supercritical conditions, and future products such as integration of hybrid Brayton Microturbine, CHP and full Solar Combined Cycle.

Fig. 1: HelioFocus large Dish/Booster prototype.

High-Temperature Thermal Storage using a Packed Bed of Rocks

I = individual member country activities of interest to SolarPACES	X
M = member country task-shared activities of interest to SolarPACES	
T = SolarPACES task-shared activities	
C = SolarPACES cost-shared activities	

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Participants: ETH Zurich, Airlight Energy,

Website: http://www.pre.ethz.ch/research/projects/?id=airlight_stor

Funding: Swiss Federal Office of Energy

A simple yet effective storage system utilizing a packed bed of rocks was designed, built, tested, and modeled for storing thermal energy of an air-based solar receiver. Its main advantages are: 1) abundant and economical storing material; 2) applicability in a wide temperature range, with limiting temperatures given by the rock's melting point; 3) direct heat transfer between working fluid and storage material; 4) no degradation or chemical instability; 5) no safety concerns, and 6) elimination of chemicals and corrosive materials.

Figure 1 shows the prototype design and the experimental setup. It has the outline of a truncated cone with a dodecagon cross section. The walls are made of concrete and the whole storage is immersed in the ground for higher mechanical stability. The prototype has a total height of 4 m and the diameter of the circle inscribing the dodecagon varies from 4 m at the top to 2.5 m at the bottom. The storage is filled with rocks with a mean diameter of approximately 3 cm. During charging mode, hot air from the solar field enters from the top and flows downwards, ensuring temperature stratification in the storage. During discharging mode, air at ambient temperature enters at the bottom and flows upwards. Figure 2 shows a scheme of the geometry and a photo of the prototype.

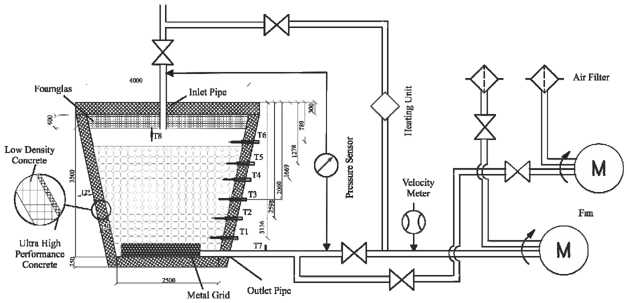

Fig. 1: Concrete tank of the packed bed thermal energy storage prototype

Fig. 2: The storage geometry and prototype

A dynamic numerical heat transfer model was formulated for separate fluid and solid phases and variable thermo-physical properties, and validated with experimental results. The validated model was further applied to design and simulate an array of two industrial-scale thermal storage units, each of 6.6 GWh_{th} capacity, for a 35 MW_{el} concentrated solar power plant during multiple charging/discharging cycles, yielding 95% overall thermal efficiency.

Reference:

Haenchen M., Brückner S., Steinfeld A., "High-Temperature Thermal Storage using a Packed Bed of Rocks - Heat Transfer Analysis and Experimental Validation", *Applied Thermal Engineering*, Vol. 31, pp. 1798-1806, 2011.

Optimization of thermal storage components and equipment

I = individual member country activities of interest to SolarPACES	X
M = member country task-shared activities of interest to SolarPACES	
T = SolarPACES task-shared activities	
C = SolarPACES cost-shared activities	

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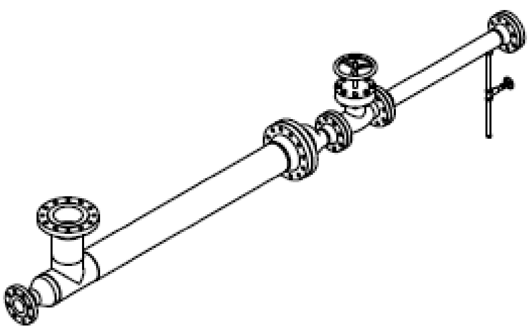
Aligned with the objectives of the European Commission Technology Roadmap 2010-2020, Ciemat, by its Concentrating Solar Systems Unit, ~~is~~ has been working on developing and optimizing thermal energy storage systems for several years. Today there are two main R&D lines related to thermal storage development:

(a)<u>Components design and optimization</u>:

A new design concept, outlined in 2010, for **latent heat storage** with phase change materials with low thermal conductivity has been developed and patented in 2011. Offering an alternative to the actual fin tube design and steam drums, this new design assures an efficient heat transfer between the two-phase HTF flow and PCM due to its high heat exchange area, acts also as steam separator in discharge and implies a low steam HTF pressure drop in charge. Additional mechanisms ~~of~~ for improving thermal conductivity of the PCM, like introducing metal foams, are allowed which would reduce the required size for a given capacity.

(b)<u>Experimental evaluation of components, equipment and procedures:</u>

The test facility with molten salts as heat transfer fluid erected at the Plataforma Solar de Almeria (PSA) has been improved during 2011. This facility is composed of two installations: one small device where valves, auxiliary heating trace and piping can be tested (Figure 1-A) and a bigger one where also vertical pumps and control strategies can be studied and tested (Figure 1-B). Testing procedures for valves have been outlined and several companies have already shown interest in testing components in these loops., Ciemat is currently collaborating with a total of 12 companies, through their respective Structural Material Division, to study the compatibility of different structural materials due to corrosion with molten salts.



(A)

(B)

Fig. 1: Multipurpose molten salt test facility: (A) device with no circulation; (B) molten salt loop installation.

Ciemat has been actively involved in the international activities for defining standard testing procedures to characterize thermal storages, both at prototype level (under the 7FP-EU project SFERA) and at commercial level (by the Spanish certification body AENOR and ASME PTC52).

Other Ciemat´s activities during 2011 worth mentioning were its collaborations with the European initiatives EERA (European Research Alliance) and KIC (Knowledge and Innovation Communities).

References:

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Rojas, E., Bayón, R., Adinberg, R., Fabrizi, F., Hutter, C., Laing, D., Py, X., *Towards standardization of testing storage prototypes*, 17th SolarPACES International Symposium. Granada, Spain, 20-23 September 2011

ITES – Storage System for Direct Steam Generation

I = individual member country activities of interest to SolarPACES	**X**
M = member country task-shared activities of interest to SolarPACES	
T = SolarPACES task-shared activities	
C = SolarPACES cost-shared activities	

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Funding: Partly funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU)

Cost effective storage systems demand the adaptation of the storage technology to the heat source and the consumer. For direct steam generation, there is a significant advantage, when specially adapted storage modules for preheating, evaporation and superheating are being applied. In the ITES-project a complete storage system for direct steam generation with specially adapted storage modules was developed. For preheating and superheating, the concrete storage technology developed by Ed. Züblin AG and DLR is applied, while for the evaporation section a PCM-storage is developed by DLR. A demonstration system with a total capacity of 1 MWh was tested in a DSG-testloop at Endesa's power plant Litoral in Carboneras, Spain.

The concrete storage technology, successfully developed for trough power plants with thermal oil as heat transfer fluid, has been successfully adapted and demonstrated for water/steam as heat transfer fluid. However the economic analysis showed that in contrast to the application with thermal oil, in DSG concrete storage is too expnsive due to the low usable temperature difference and the high system pressure.

The PCM-storage used for evaporation/condensation of the water/steam fluid, uses sodium nitrate as phase change material. The PCM storage module applies a specially developed finned tube design with aluminum fins, to reach the required high heat transfer rates. The PCM has a melting temperature of 305 °C; this leads to a steam pressure of 107 bars during charging and 80 bars during discharging. The PCM-storage demo-module uses 14 tons of salt with a latent heat capacity of approx. 700 kWh (see Fig. 1).

The 1 MW-demonstration storage system, build up of the PCM-storage module and the concrete superheater module was successfully tested in coupled operation as well as in single module operation. The focus for testing was on the 700 kWh PCM-storage.

The operation of this PCM storage module for evaporating water in constant and sliding pressure mode was successfully demonstrated. Three different operation modes regarding flow for discharging the PCM storage have been tested successfully, showing potential for future cost reductions for the complete storage system. Here, either only the recirculation pump or even the complete circulation cycle including the steam drum could be eliminated. Good system operability of the systems was achieved.

It can be concluded, that PCM storage operation in a water steam loop with power plant operation parameters is feasible. Very high discharge rates have been proven, the test results are reproducible, showing cycling stability of the system. Operation can be conducted in various modes. The best practice needs to be determined for the specific applications. Hydraulic balancing of the circulation system is an issue for further investigation, to increase the operation range.

The next generation DSG-storage system will involve PCM-storage in connection with a three-tank molten salt storage system for preheating and superheating. This is currently under development in cooperation with industrial partners, including, as the next step, a scale up to pre-commercial scale of 10-20 MWh capacity.

Fig. 1: PCM-storage demo-module in Carboneras

References:

D. Laing, C. Bahl, M. Eickhoff, M. Fiß, M. Hempel, M. Meyer-Grünefeldt, (2011). Test Results of a Combined Storage System for Parabolic Trough Power Plants with Direct Steam Generation, ASME 5th International Conference on Energy Sustainability, Washington D.C., USA.

Laing, Doerte und Bahl, Carsten und Fiß, Michael und Hempel, Matthias und Meyer-Grünefeldt, Mirko und Eickhoff, Martin und Stückle, Andreas (2011) TEST AND EVALUATION OF A THERMAL ENERGY STORAGE SYSTEM FOR DIRECT STEAM GENERATION. SolarPACES 2011, 21. -24. Sept. 2011, Granada, Spanien.

OPAC Optical Aging Characterization Laboratory

I = individual member country activities of interest to SolarPACES	X
M = member country task-shared activities of interest to SolarPACES	
T = SolarPACES task-shared activities	
C = SolarPACES cost-shared activities	

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The commercialization of concentrating solar power technologies lead to the many worldwide industrial projects and CSP power plants feeding electricity into national power networks. The technical challenges of the real working conditions, financing and keeping the power efficiency goals puts a lot of pressure on manufacturers and plant operating companies. The need for quality and lifetime guarantees of the components increases more and more. Those guarantees can only be given with appropriate standardized testing methods. Up to now, standards regarding the components for CSP technology specifically do not yet exist, which is why currently standards from similar application fields are being adopted. But these standards are not always adequate for this application. Work on improving this situation is being carried out by the SolarPACES Task groups, where various research institutions work together with the industry.

At the Plataforma Solar de Almería (PSA) in Spain the OPAC (Optical Aging Characterization Laboratory) is a collaborative project between CIEMAT and DLR, which is dedicated to defining appropriate qualification and test methods with focus on one of the main CSP components, the reflector and the mirror-material itself. The aims of this project are:

- To establish the most suitable instruments and methods for optical characterization and aging tests of CSP reflectors.
- To establish adequate procedures, standards and guidelines for optical characterization and aging tests of CSP reflectors.
- To do research on degradation processes of materials used in CSP under accelerated conditions and outdoor exposure with the goal of establishing lifetime prediction models.
- To offer technical support and services to the industry.
-

To do this, the laboratory is equipped with a set of common instruments and in-house prototypes of artificial aging chambers, outdoor exposure test stands and optical analysis equipment. Great advancement has been achieved in finding artificial aging tests that correlate to degradation processes in outdoor exposure of low-cost aluminum mirrors and derive a lifetime prediction model. Also, various studies regarding anti-soiling coatings on glass mirrors are being performed as well as studies about the effects of different aggressive exposure sites with outdoor test stands in coastal, industrial and desert regions, in Europe and North Africa (Fig. 1).

While also developing improved optical measurement systems, another main achievement of 2011 (in collaboration with NREL) has been the publication of an interim guideline on the topic of reflectance measurement methods using commercially available instruments. It is a summary of current knowledge and experience that can serve as a basis for further advancement towards standardization. The document is currently awaiting revision in order to proceed to the next stage, where contributions from other institutions and industry will be implemented once technical discussions have resolved current opinion dicrepancies. It can be downloaded on the SolarPACES homepage of Task III (http://www.solarpaces.org/Tasks/Task3/reflectance_guideline.htm).

Fig. 1: Outdoor test stand at PSA in Tabernas, Spain

SFERA: Solar Facilities for the European Research Area

I = individual member country activities of interest to SolarPACES	
M = member country task-shared activities of interest to SolarPACES	X
T = SolarPACES task-shared activities	
C = SolarPACES cost-shared activities	

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DIN (DE), UPS Toulouse (FR), AUNERGY (ES), CEA (FR), INESC-ID (PT)
Start : 1 July, 2009
Duration: 48 months

Funding: European Commission, approx. 7.4 M€

To achieve a secure and sustainable energy supply, and in view of growing climate change concerns, the EU has taken on the role of Kyoto Protocol promoter and set ambitious goals to achieve a large share of renewable energy in the European market. In particular, March 2009 saw European leaders sign a binding EU-wide target to source 20% of their energy needs from renewable sources such as hydro, wind and solar power by 2020. Solar energy, as a primary source of renewable energy, will likely contribute a major share.

There is, however, a need for further investment in research, development and application of concentrating solar systems involving a growing number of industries and utilities in global business opportunities.

The purpose of SFERA is thus to integrate, coordinate and further focus scientific collaboration among the leading European research institutions in solar concentrating systems and offer European researchers and industry access to the best-qualified research and test infrastructures.

Through coordinated integration of their complementary strengths, efforts and resources, the project is working to increase the scientific and technological knowledge base in the field of concentrating solar systems in both depth and breadth, provide and improve the research tools best-suited for the community of scientists and engineers working in this field, and increase the general awareness – especially of the scientific community – of the possible applications of concentrated solar energy.

The overall goal of these efforts is to create a unified virtual European Laboratory for Concentrating Solar Systems, easily accessible to interested researchers, and thus serving as the structural nucleus for growing demand in this field. Such a European Solar Laboratory would also contribute to a sustainable, secure European energy supply and to a firm basis for global competitiveness of European suppliers of technology in this field.

Five of the project partners – CIEMAT-PSA, DLR, PROMES-CNRS, ETH and PSI –are already collaborating in the SolLAB virtual laboratory consortium, which has initiated several networking activities since its creation in 2004. ENEA and WEIZMANN now join the consortium, thus looking to consolidate a partnership as the reference European Solar Laboratory.

The project incorporates transnational access, networking and joint research activities. Researchers have access to five state-of-the-art high-flux solar research facilities, unique in Europe and in the world. Access to these facilities will help strengthen the European Research Area by opening installations to European and partner countries' scientists, thereby enhancing cooperation. It will also improve scientific critical mass in domains where knowledge is now widely dispersed, and generate strong Europe-wide R&D project consortia, increasing the competitiveness of each member.

The joint research activities aim to improve the quality and service of the existing infrastructure, extend their services and jointly achieve a common level of high scientific quality. All facilities currently use their own procedures to perform tests and experiments under concentrated sunlight and have developed their own devices to measure flux and temperature as the most relevant and complex signals in these installations. In addition, new facilities that use artificial light sources to simulate the concentrated sunlight have recently become available and need to be qualified to assess their best fields of application.

To improve the quality of their installation test services, the partners will, for example, cooperate to establish common guidelines on how to perform testing and develop and exchange best-practice approaches. They have included the competences of the DIN, the German standardization institution, in order to come up with a systematic and professional approach in this field.

In addition, a set of five networking activities will be undertaken. These include the organization of training courses and schools to create a common training framework, providing regularized, unified training of young researchers in the capabilities and operation of concentrating solar facilities. Communication activities will seek to both strengthen relationships within the consortium, creating a culture of cooperation, and to inform the general public, academia and especially the industry, about what SFERA is and what services are offered. This will give many potential users the opportunity to become aware of the existing possibilities for making use of the SFERA infrastructures.

Development of guidelines for standards for CSP components

I = individual member country activities of interest to SolarPACES	X
M = member country task-shared activities of interest to SolarPACES	
T = SolarPACES task-shared activities	X
C = SolarPACES cost-shared activities	X

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Participants: SolarPACES members

Funding: in-kind

This activity started in 2008 with two SolarPACES TASK III workshops to define objectives and a roadmap for the development of standards for CSP components. The main goal is to evaluate known procedures and methods for component qualification and analyze the needs for new methods. Based on this, guidelines should be developed for standards for CSP components.

The following four working groups were established:

a) Guidelines for reflectance characterisation
b) Guidelines for mirror panel and modules characterisation
c) Guidelines for receiver performance measurements
d) Guidelines for durability testing

In 2011 two SolarPACES workshops were organized, both in Granada, Spain. The first was held on February 21st with 50 participants and the second on September 19th, in conjunction with the SolarPACES Symposium, with 56 participants. The intensive discussion between industry members and research institutions showed a wide agreement in the developed methods. Since 2010, this activity is also financially supported by SolarPACES in a 3year project.

In group a) a round robin test has been conducted to pre-define guidelines for reflectance measurements. The results showed the validity of the currently proposed method but also revealed the areas where an improvement of the state of the art is still needed. A core team prepared a proposal for the most promising procedure, which then was published as a first interim draft SolarPACES Guideline document in spring 2011. Comments were provided over the course of the year and discussed in the second workshop. Because some points of discussion were still to be agreed on, a technical meeting and a second round robin test were planned for 2012 with the mission to finalize the guideline to international consensus and transform it into a proposal for standardization at IEC by the end of 2012.

Group b) showed significant advances and will finalize the draft guideline on mirror module shape measurements by autumn 2012.

Group c) will also apply for a SolarPACES fund with the objective to finalize a guideline in autumn 2013.

The next workshop was announced for autumn 2012 in combination with the SolarPACES Symposium in Marrakech, Morocco.

Guideline for Standard for Reflector Shape Analysis

I = individual member country activities of interest to SolarPACES	X
M = member country task-shared activities of interest to SolarPACES	
T = SolarPACES task-shared activities	X
C = SolarPACES cost-shared activities	X

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Funding: different sources, BMU, SolarPACES, industry

The shape and relative orientation of the mirror used for concentrating the sunlight onto the receiver determines how much of the specularly reflected beam radiation hits the receiver. This fraction is usually denominated the “intercept factor” (IC). The intercept factor depends on the reflector geometry as well as on the geometric parameters of the receiver (size, position) and on the sun position and tracking system.

In view of the supply chain and system design, it is relevant to characterize the mirror shape quality as such, independently of the configuration of the rest of influence parameters on the intercept factor. In previous work performed at the majority of the institutions active in CSP development, the surface slope has been measured with various strategies and technologies. Common techniques are

1. deflectometric techniques,
2. laser beam reflection methods, and
3. 3D point measurements.

It is useful to evaluate the mirror surface slope or its deviation from the design geometry. For this reason it has proven most practical to use the first two methods for detecting the orientation of the reflex on the mirror itself. Successful examples are the QDec, AIMFAST, TOP and VShot methods of DLR, NREL and SANDIA respectively, as well as further laser reflex measurements applied by ENEA, Flabeg, Siemens and others.

The methods are applicable to trough mirrors as well as any other concentrator geometry variant (heliostats, linear-Fresnel, dish). The wider and standardized introduction of mirror shape quality measurements based on the new guideline will contribute to:

- increase and maintain mirror quality and power plant output of CSP plants, and

- enhance the development of new competitive materials, products and suppliers.

The required accuracy of slope measurements for CSP mirrors is 0.2-1 mrad. For successful measurements, not only the appropriate methods are required, but also the instructions for their application, including sample preparation, preferred configurations, and evaluation strategies. The effect of the measurement position (e.g. vertical/horizontal), support frame, and mounting forces must be considered for reproducible measurement results in different boundary conditions to achieve comparable evaluations.

Based on the measurement results and the ray-tracing analyses, it has been proposed to specify mirror shape quality with the standard slope deviation parameters SDx and SDy, and standard focus deviation FDx and FDy in transversal and longitudinal directions respectively. For dish systems polar coordinates are common. These values are the root mean square (rms) of thousands of individual measurements of slope deviation from the design shape on the reflector surface. This specification replaces previously used definitions related to laser-beam intercept factors on the receiver size without the direct need of changing measurement procedures but with much higher significance as the quality parameter for a key element of CSP technology.

As objective for the glass reflector for high performance trough collectors a typical value for the standard slope deviation SDx is 1.5-2.5 mrad, and for the standard focus deviation FDx in transversal direction about 15% of the absorber diameter.

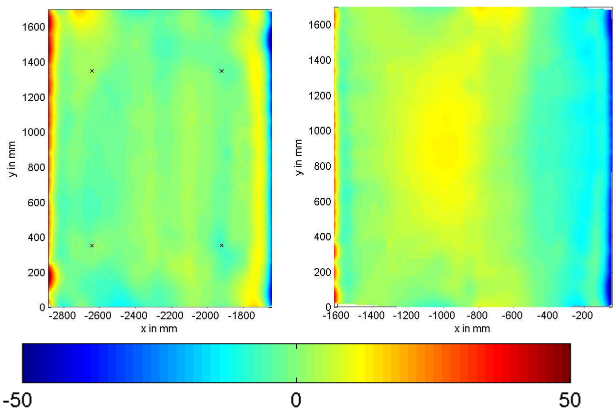

Fig. 1: Example of a QDec measurement result of the spatial distribution of the transversal focal deviation (FDx) for the surface analysis of a pair of mirrors (RP3 inner and outer), scale in mm

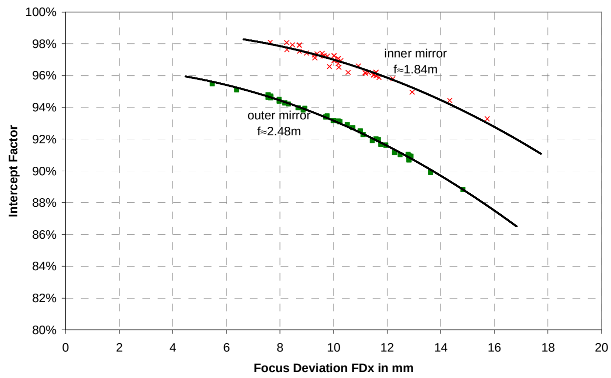

Figure 2: Sun intercept factor - ray-tracing results for EuroTrough (RP3) mirror panels assuming a typical sunshape and including typical tolerances for the rest of the collector components, for 0° incidence angle

Minimum specification of RP3 mirror panels should fulfill FDx of below 12 mm. Current state of the art for the standard focus deviation in RP3 mirror production is below 10 mm, often already below 8 mm, and relevant potential is even below, with relevant impact on the solar field performance. A surface area of at least 98.5% of the mirror aperture area should be evaluated. The deflectometric method has been successfully transferred to industrial application by the mirror manufacturers, as well as for solar field assembly quality control.

The draft guideline on mirror shape for CSP systems will be available from SolarPACES for wider commenting and development during the year 2012.

References

E. Lüpfert, S. Ulmer: Solar Trough Mirror Shape Specifications, SolarPACES Conference, Berlin, September 2009

6. Task V: Solar Resource Assessment and Forecasting

Task Representative:
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Task Participants:

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- Canada: Environment Canada, CANMET
- European Union / Italy: Joint Research Center (JRC)
- France: EdM/Armines, LASH-ENTPE
- Germany: DLR, Suntrace GmbH, University of Applied Sciences Ulm, University of Oldenburg (EHF)
- Norway: University of Agder
- Slovakia: GeoModel s.r.o.
- Spain: CIEMAT, CENER, University of Jaén, University of Navarra
- Switzerland: Meteotest, University of Genève (UNIGE)
- USA: NREL (Operating Agent), NASA, SUNY

6.1 Nature of Work and Objectives

"Solar Resource Assessment and Forecasting" is an IEA Task under the Solar Heating and Cooling (SHC) Programme Implementing Agreement with Dr. David Renné from NREL as Operating Agent. There the Task is counted as Task-46. The IEA SolarPACES ExCo also guides the Task, where it is called Task V and is represented by Dr. Richard Meyer of Suntrace GmbH. It further maintains collaboration with the IEA Implementing Agreement PVPS (Photovoltaic Power Systems).

The Task is a follow up of the earlier SHC-Task-36 named "Solar Resource Knowledge Management". The title change reflects the changing priorities. The task now focuses primarily on the two most important topics in the field of solar radiation for solar energy applications: For financing the bigger and bigger projects sound solar resource assessments are more and more important. And for operation of the many MW installed power forecasting of solar radiation is receiving high attention from plant and grid operators. In SolarPACES it remains as Task V, but with a new title.

The scope of work of the task addresses several more solar resource topics even beyond solar forecasting and resource assessment. But many are related to the main topics. It covers satellite-derived solar resource products, ground-based solar measurements also covering topics not picked up in Task 36 like measuring circumsolar radiation.

The Task equally supports solar thermal heating and cooling, photovoltaics and concentrating solar power applications. However, for best serving the objectives of SolarPACES this report focuses on direct solar radiation, which can be concentrated.

The four objectives of this Task are:

- Evaluate solar resource variability that impacts large penetrations of solar technologies;
- Develop standardized and integrating procedures for data bankability;
- Improve procedures for short-term solar resource forecasting, and
- Advance solar resource modeling procedures based on physical principles.

Achieving these objectives would reduce the cost of planning and deploying solar energy systems, improve efficiency of solar energy systems through more accurate and complete solar resource information, and increase the value of the solar energy produced by solar technologies.

The Task is now structured in four subtasks:

- Subtask A: Solar Resource Applications for High Penetrations of Solar Technologies
- Subtask B: Standardization and Integration Procedures for Data Bankability
- Subtask C: Solar Irradiance Forecasting
- Subtask D: Advanced Resource Modeling

6.2 Activities During 2011

A Task Experts Meeting was held on March 1-2 at DLR in Stuttgart, Germany. This was the final meeting of SHC Task-36 and in parallel the planning meeting for SHC Task-46.

Another full Task Meeting was held on September 2nd following the ISES Solar World Congress in Kassel, Germany. This was the initial Meeting of SHC Task-46 and helped to further shape the new Task work plan, which was approved by the SHC ExCo in November.

After the SolarPACES Symposium 2011 in Granada a one-day workshop of Activity B.1 for new and advanced solar measurements took place hosted by DLR at PSA.

The 1st International Conference on Energy Meteorology in Queensland, Australia, was co-chaired by several Task participants.

A number of Task-related papers were presented by task participants at the SolarPACES Conference in Granada, and the Solar World Congress in Kassel. Instead of reviewing and summarizing the most important works of Task participants of last year, this year's report is focusing on the description of the new work plan.

6.3 Subtask A: Solar Resource Applications for High Penetration of Solar Technologies

This Subtask is led by Richard Perez of University of Albany (SUNY, USA). It aims to develop data sets necessary to allow better understanding short-term resource variability characteristics, in particular up and down ramp rates. This should help to better manage large penetrations of solar technologies in the grid system. This work is focused toward PV systems, which react almost instantaneously to cloud passages over individual panels and thus lead to highly variable plant output. This is a burden for the stability of the grid. But the information about variability may also be useful for solar thermal and CSP systems. Their intermittency due to variable solar resources has less impact due to their higher inertia. Nevertheless it has some effects especially on plant control and could require higher co-firing rates to meet the demands.

Subtask A is structured into three main activities. The first concentrates on solar resource aspects itself, the second cares about combination of solar with other renewables to match demand especially in island systems and the third cares about the integration of intermitting solar and wind production into the grid. In detail the following is planned:

6.3.1 Activity A1: Short-Term Variability

A1 is led by Hans Georg Bayer of University Agder (Norway). This activity is concerned with the spatial and temporal characterization of high frequency intermittency at time-scales of 15 minutes or less. It looks at ramp rates of solar radiation, and how this variability may impact the operation of solar technologies and their deployment on local power grids.

6.3.2 Activity A2: Integration of solar with other RE technologies

This activity is led by CENER (Spain). It deals with hybrid power generation involving solar and other renewable technologies (e.g., wind, biomass). Hybrid generation has pertinence to various scales from remotely operating hybrid installations, to autonomous and/or interconnected micro-grids and larger scales. The focus of this activity will be placed on weather data and irradiance data requirements to address such questions. Initially smaller scale issues – autonomous hybrid systems are the main point of interest.

6.3.3 Activity A3: Spatial and Temporal Balancing Studies of the Solar and Wind Energy Resource

A3 is under the lead of David Pozo of Universidad de Jaén (Spain). This Activity is concerned with the analysis and modeling of solar and renewable resource data to address: (1) the spatial balancing of the solar resource (both GHI and DNI driven resources) across various distance scales; (2) the spatial and temporal balancing of both the solar and wind resources across various distance scales, and (3) the determination of the requirements for solar radiation forecasting to allow better balancing of the grid.

6.4 Subtask B: Standardization and Integration Procedures for Data Bankability

This subtask is coordinated by Carsten Hoyer-Klick of DLR (Germany). It addresses data quality and bankability issues related to measurement practices and also the use of modeled data, which covers satellite-derived and purely model-derived solar radiation products.

The topics of Subtask A are structured in five activities. The first deals only with measurements. The second activity should improve and standardize quality check procedures, gap-filling, flagging of errors and data formatting. Activity B3 cares about the fusion of various solar resource data sets, while B4 integrates auxiliary meteorological products, which are needed for proper performance simulation of solar energy systems. Activity B5 defines and analyses the uncertainty of solar radiation data at various temporal and spatial scales.

6.4.1 Activity B1: Measurement best practices

This Activity is led by Stefan Wilbert of DLR (Germany) working at its lab in Almería, Spain. The main goal is to agree best practices for obtaining qualified solar measurements. A handbook should describe, what is needed to provide bankable data for large solar projects. It includes also better characterization of commonly used instruments like the Rotating Shadowband Irradiometers (RSIs) and other not as yet standardized types of solar radiation sensors. The Activity supports standardization of such instruments and their use in connection to WMO and the respective standardization bodies.

Beyond this also newer solar radiation measurands not yet widely used in solar energy, but relevant for more detailed analysis of some systems should be defined. An example is the circumsolar ratio, which is of relevance for systems with high concentration factors.

For all kinds of measurements covered in this activity the analysis of uncertainty plays an important role. The goal is to follow the guide on General Uncertainty of Measurements (GUM) to learn more about absolute accuracy of the various instruments. It needs to be differentiated at which sun elevation, with which sort and age of calibration and under which instrument cleanliness a solar radiation measurement was taken, to estimate the uncertainty of individual values. Due to the randomness of some errors the uncertainty of mean values partly averages out, but it needs to be known for qualified data.

6.4.2 Activity B2: Gap-Filling, QC, Flagging, Data Formatting

This Activity lead by Carsten Hoyer-Klick of DLR (Germany) should improve quality check (QC) procedures and documents best practices of their application. QC is an essential exercise before any further analysis of measured data, but could also be applied to model-derived time-series data.

B2 covers also the related topic of filling data gaps for reaching complete time-series. This is often needed for performance simulation, which requires continuous input data.

Related to QC is also the flagging of data values, which are classified as erroneous. In professional data sets for each value the quality should be indicated. To allow easier understanding, international collaboration and exchange of data various existing conventions should be standardized.

Also it would be very helpful for good collaboration of data providers and performance simulation engineers to have common formats for solar radiation and other meteorological data. Therefore, this activity also cares for definition of common data formats in this field.

6.4.3 Activity B3: Integration of data sources

This Activity is led by CIEMAT (Spain). It should explore procedures of combining different data sets, such as short-term ground measurements with long-term satellite derived data. This should bring over the quality of potentially better ground-measured data sets to the modeled data sets, which bring in the long-term climatic view. The combined long-term data set then typically are used to derive the long-term climatological average of the various radiation products. Having realistic long-term time series available also allows to make use of more sophisticated approaches in modeling potential cash flows from solar energy projects. Instead of simply applying a single typical meteorological year (TMY) many real historic years can feed performance simulation models. This would be an alternative to using just a P70 or P90 year derived from inter-annual variability for risk analysis.

Sub-activities in B3 involve:

- acquiring ground-measured data and satellite data covering parallel period of records,
- the review of existing methods for integration of data sources,
- the definition of statistical parameters for use in characterizing the combination of ground-based and satellite-derived data,
- the criteria for selection of useable data for data fusion,
- the validation of the procedure and further improvement.

6.4.4 Activity B4: Evaluation of Meteorological Products

B4 led by GeoModel s.r.o. (Slovakia) is aiming to build on B3 and adds auxiliary meteorological parameters, which are of use for simulating the performance of solar energy systems. Such parameters are air temperature, humidity, wind speed, gusts and wind direction. For some solar plants also air pressure plays a role, e.g. for the cooling process.

In this activity the historical use of TMY data will be evaluated in the context of better practices for simulating solar system design and output. Recommendations for alternative approaches to TMY data will be made, given that TMY data sets do not allow for evaluation of extreme events. Also higher time resolutions should be considered. Sub-activities are:

- reviewing the use of TMY in industry and financing,
- based on the results of the review create TMYs and improvement of the same,
- standardize formats of TMY datasets and
- the possibility of developing multi-year data sets for improved risk analysis.

6.4.5 Activity B5: Data uncertainty for various temporal and spatial resolutions

Activity B5 lead by Richard Meyer of Suntrace (Germany) has the objective to analyze mainly the uncertainty of modeled solar resource data, which is mostly satellite-derived, but could be also purely model-derived data products. It should also deal with ground-measurement adapted modeled data sets, such as those derived from integrated data with procedures developed in B3.

Due to the fact that many sources of uncertainty in modeled data are of somehow random nature by integrating over longer time-periods deviations between the modeled and the reference measurements are averaging out. E.g., the random error of partly cloudy pixels or model boxes averages out, when not just the instantaneous values are inter-compared, but both measurements and satellites are averaged over 1 to 3 hours. Or the parallax error due to misplaced cloud shadows in satellite data averages out well when only daily values are compared.

A similar statistical effect can be seen in spatial averaging. Often results of hourly values are much better, when the satellite-derived values are averaged over an area of 10 km by 10 km instead of taking the 1 km by 1 km satellite resolution.

Thus, the benchmarking of model-derived data products always must clearly indicate which type of spatial and temporal averaging it refers to. Systematic tests should be done to show various effects. This activity also should contribute to the improvement of best practices for risk analysis of large scale solar projects.

6.5 Results of Subtask C: Solar Irradiance Forecasting

The Subtask C on solar irradiance forecasting is co-ordinated by Elke Lorenz of University Oldenburg (Germany). Solar radiation forecasting provides the base for management and operations strategies for many solar energy applications. With high grid penetration such as the current trend in Germany, solar power forecasting gets essential for operating the grid and of course also has significant effect on market prizes.

Depending on the application and its corresponding time scales, different forecasting approaches are appropriate. In this subtask forecasting methods covering time-scale from several minutes up to seven days ahead will be developed, tested and compared in benchmarking studies. The use of solar irradiance forecasting approaches in different fields will be investigated, including PV and CSP power forecasting for plant operators and utility companies, as well as irradiance forecasting for heating and cooling of buildings or districts.

The Subtask is basically grouped in two Activities. The first one involves the meteorological methods to do short-term forecasts up to 7 days. The second Activity aims for integration of these forecasting results into operations.

6.5.1 Activity C1: Short-term forecasting up to 7 days ahead

This activity is co-led by Elke Lorenz of University of Oldenburg (Germany) and by Richard Perez of SUNY (Albany/USA). Development and improvement of methods currently used to forecast GHI and DNI are major tasks in C1. Different forecast horizons, ranging from minutes up to several days ahead are addressed using specific methodology and data. The focus on the specific needs of the Activity is further structured in five Sub-Activities which cover different forecasting approaches. Procedures can be separated by the data sources, corresponding methods and time scales used. A sixth Sub-Activity covers the comparison of these approaches. A verdict should be reached on which sort of method is most accurate for which forecasting horizon. Such method should also allow to compare which solar radiation parameter is best forecasted in which way.

6.5.2 Activity C2: Integration of solar forecasts into operations

This activity is led by IrSoLAV (Spain). It examines the important issue of how solar forecasts are used for different applications, including utility operations, management of PV or CSP power plants, and thermal management of buildings. A critical aspect of this task is to seek input from users, e.g. utility operators on the specific types of irradiance or power output forecasts they need in order to improve system operations and reduce the overall cost of energy and maximize the use of renewable energy within the system.

To link the Subtask with the needs of industrial users it is planned to hold a designated workshop, or forum at solar energy conferences. Addressed industry representatives include CSP and PV system operators, energy traders, utility companies and the building sector. This sub-activity is also connected to IEA/PVPS Task 14 and a common task workshop has been planned.

The use of solar irradiances forecasts for different applications will be investigated in this sub-activity. Out of this, showcases for various applications of solar radiation forecasting can be given. The studies should also investigate the influence of forecast uncertainty on the energy yields. The following actions are planned to be addressed:

- PV power forecasting,
- CSP forecasting,
- CPV forecasting,
- management of building´s heating systems,
- management of solar district heating,
- solar power forecasting for electric utilities,
- solar/wind balancing study (in cooperation with sub activity A3.6).

In addition, a benchmarking study for different PV power forecasting approaches is planned.

6.6 Results of Subtask D: Advanced Resource Modeling

The Subtask on advanced resource modeling is led by Philippe Blanc of Mines Paris-Tech (France). Although most of the work in Task 36 involved the testing and evaluation of existing solar resource methodologies, some specific new methodologies have been identified that could be developed within a new task. These methodologies are driven by specific information requests from energy project developers and planners.

The Subtask is divided into three activities. D1 should further improve methods to better derive historic solar radiation data from satellites and models. The second Activity aims to analyze the worldwide distribution of solar resources aiming at an integrated assessment of global and regional renewable energy scenarios. The third activity will study the impact of climate change on solar resources, from a historical perspective as well as the estimate of future impact.

6.6.1 Activity D1: Improving existing solar radiation retrievals

Led by Tomas Cebecauer of GeoModel s.r.o. (Slovakia) the objective of this activity is to improve state-of-the-art solar radiation modeling and develop new modeling approaches. It should look for alternative sources for the input of parameters to improve the accuracy and/or to increase the spatial, spectral and angular resolutions of solar resource data sets derived from satellite. An overview of the different advanced solar radiation available will be given as well the corresponding requirements of their input parameters. This task will also evaluate the latest products coming out of the U.S. National Oceanic and Atmospheric Administration (NOAA), such as the GOES Surface Irradiance Product, which offers a promising solution for providing near real-time irradiance values throughout the western hemisphere at 4-km resolution. Sub-Activities are:

- direct/diffuse transposition model (radiative transfer code for direct/diffuse and angular distribution of irradiance),
- circumsolar (sun shape) analysis,
- spectrally resolved irradiance,
- enhanced atmospheric parameters for radiative transfer code based modeling: aerosol optical depth, enhanced cloud parameters, including 3-D cloud characterization, and
- other model upgrades: pixel disaggregation (down-scaling solar irradiation data) for high spatial resolution solar map, etc.

6.6.2 Activity D2: Global solar resource data sets for integrated assessment of worldwide and regional renewable energy scenarios, with a special focus on CSP and solar heating technologies

This activity is led by Carsten Hoyer-Klick of DLR (Germany). It examines approaches for determining worldwide renewable energy potentials, in particular global potentials, for use in renewable energy scenario modeling. The Activity also looks at the impact of up-scaling fine-resolution data into courser global grids, to see if the removal of sub grid variability introduces biases to the answers.

6.6.3 Activity D3: Long-term analysis and scenarios of solar resource trends and variability

This activity co-led by Paul Stackhouse of NASA-LaRC (USA) and Jan Remund of Meteotest (Switzerland) should study long-term solar data sets, both observed and satellite-derived and also climate change scenarios for their effects on solar radiation parameters.

It will reassess episodes of "global dimming" and "global brightening". These are important for evaluating potential long-term cash flow implications from solar energy projects. The uncertainties of the variability are characterized from large continental to regional scales. Efforts will be undertaken to link the results of IPCC climate change scenarios to predictions of future solar resource variations.

The following Sub-Activities are planned:

- Evaluation of the influence of leading atmospheric patterns such as the North Atlantic Oscillation (NAO) and the El Nino Southern Oscillation (ENSO) on the inter-annual variability of GHI and DNI. Examine the magnitude of this variability relative to the uncertainties associated with measurements or satellite-derived data products. Also, include an evaluation of the long-term variability of the data sets as a function of scale in relation to measurement uncertainties. Evaluate accuracies required to detect long-term changes. Reassess as new improved data sets become available. Assess and provide statistical variability information to improve "bankability".
- Evaluation of the global general circulation model (GCM) baseline runs undertaken for the Intergovernmental Panel of Climate Change (IPCC) in respect to the variability of surface and satellite derived observations of solar radiation. Then assess future climate changes in solar irradiances over a number of models and standard scenarios relative to the baseline runs at various horizontal scales. Assess climate model changes relative to the uncertainties found in baseline runs. Is the likelyhood assignation possible? What statistical distribution would be relevant to bankability?

7. Task VI:
Solar Energy and Water Processes and Applications

Operating Agent:

Julián Blanco
Plataforma Solar de Almería. CIEMAT

Contributions:

Christian Sattler (DLR, Germany)
Reda Abdel Azim Younes (NREA, Egypt)

7.1 Nature of Work & Objectives

Water and energy issues and their mutual interaction problems are clearly becoming an issue of increasing worry in many world regions. This fact, combined with the habitual coincidence of water problems and high levels of solar radiation at many Sun Belt locations, was the main argument to the recent creation of Task VI with the primary objective of encouraging the development of solar technologies simultaneously addressing energy and water issues.

Defined Scope of Work of this Task covers any solar radiation technology supplying either thermal or photon primary energy for water treatment, which includes:

- Brackish and seawater desalination: development of technical procedures and methodologies for removing or reducing the salt content from water using solar energy as primary energy source.
- Solar power and water cogeneration plants: effective integration of desalination technologies into solar power plants.
- Water detoxification: Removal of organic compounds, heavy metals and/or hazardous substances in general from water.
- Water disinfection: Control and/or elimination of pathogenic populations from water for human or animal consumption or irrigation.

Therefore, the purpose of the Task is to improve the conditions for solar water treatment market introduction and solve water problems, while contributing to reduced fossil-fuel consumption. The main specific focus of the activities and initiatives addressed is to demonstrate the potential of solar energy for such water applications.

7.2 Task VI Organization and Structure

Task VI is organized into the following three domains or subtasks:

Subtask VI.1. CONCENTRATING SOLAR POWER AND DESALINATION PLANTS.

The goals of this Subtask are to:

i) Collect existing knowledge and experience on hybrid power and desalination plants for application to MW-size plants;
ii) Analyze and determine the main technological characteristics of hybrid solar power and desalination plants;
iii) Promote cooperative initiatives in assessment of the specific technical and economic feasibility of hybrid solar power and desalination plants, and also identify potential follow-up demonstration case studies.

Subtask VI.2. INDEPENDENT SOLAR THERMAL DESALINATION SYSTEMS (kW-SIZE).

The goals of this Subtask are to:

i) Provide a comprehensive description of the state-of-the-art and potential applications of solar thermal desalination systems. This includes evaluating completed research programs and projects and ongoing developments in this field, as well as their economics;
ii) Publicize the knowledge among main stakeholders: solar manufacturers, process engineers, related associated industry, installers and potential customers and users;
iii) Promote collaborative initiatives for assessment of the specific technical and economic

feasibility of the most appropriate and promising technologies

Subtask VI.3. SOLAR WATER DETOXIFICATION AND DISINFECTION SYSTEMS.

The goals of this Subtask are to:

i) Provide a comprehensive description of the state-of-the-art and potential applications of solar water detoxification and disinfection systems. This includes evaluating completed research programs and projects and ongoing developments in this field, as well as their economics.
ii) To publicize the knowledge among main stakeholders: solar manufacturers, process engineers, related associated industry, installers and potential customers and users;
iii) To promote collaborative initiatives for assessment of technical and economic feasibility of specific water detoxification and disinfection problems, also identifying potential follow-up demonstration case studies.

7.3 Task VI meetings and participation in major events

Task VI is open to all IEA/SolarPACES members, who wish to actively participate in any activity described within the scope of the Task. Current Task VI activities involve active participation of institutions from Egypt, Germany, Mexico, South Africa, Spain and United States.

The 5th Annual Task VI Meeting was held in Granada (Spain) on September 19th 2011, just before the International SolarPACES Symposium on the same location. The meeting was attended by a total of 15 persons, representing 6 SolarPACES countries (Egypt, Germany, Mexico, South Africa, Spain and United States), plus Cyprus as a guest country. At the meeting, in addition to the usual administrative and organizational issues, ongoing and other possible collaborative initiatives were discussed, as well as some suggestions to increase the content and activities of the Task.

In addition, Task VI related research and activities was also presented at the following major international conferences:

- ARWADEX 2011. Water Desalination Conference in the Arab Countries. Riyadh (Saudi Arabia), 17-20 April 2011
- POLYGENERATION 2011. 2nd European Conference on Polygeneration: technologies and perspectives. Tarragona (Spain), March 30th-April 1st, 2011.
- Third Meeting of ASIA SOLAR ENERGY FORUM. Bangkok (Thailand), 30-31 May 2011
- 17th SOLARPACES Conference. Granada (Spain), 20 – 23 September 2011.
- 8th IWA Int. Conf. on Water Reclamation & Reuse. Barcelona, 26-29 Sept 2011.
- International Workshop on Advances in Disinfection Technologies, National Environmental Engineering Research Institute, Nagpur, India, February 9th 2011.

The most important achievements in 2011 are summarized in the following section, with up-to-date information about project participation, objectives, status, and relevant publications.

7.4 Summary of activities in 2011

7.4.1 Concentrating solar power and Desalination Plants

Assessment of CSP+D potential in the MENA area (T)

T = Task-shared activities by SolarPACES member countries

Contacts: Julián Blanco Gálvez, PSA-CIEMAT (julian.blanco@psa.es); Christian Sattler, DLR (Christian.Sattler@dlr.de); Reda Abdel Azim Younes (reda@nrea.eg.com)

Duration: April 2010 – March 2011

Participants: CIEMAT, DLR, NREA

Funding: 25 k€ from SolarPACES

Background: Tapping Solar Energy for electricity generation & water desalination is considered an issue with growing interest, in view of the limited water supplies in all MENA area. In the specific case of Egypt, securing water needs for both sustainable development as well as satisfaction of the domestic needs is considered a crucial issue in view of the fact that the water share/capita is around 700 m^3/year, being this figure one of the highest in the whole region. Therefore, and considering the large existing potential for CSP project development in the area, the use of solar energy to the combined production of power and freshwater became highly attractive.

Objective: The objective of this project is the realization of a technical assessment of possible configurations of Concentrating Solar Power plants with Desalination facilities (CSP+D) to optimize the production of water and electricity within the MENA (Middle East and North African) region, considering the specific coastal DNI potential and water and energy needs.

Achievements in 2011: The potential of different CSP+D configurations has been analyzed, considering the specific potential (solar resource and water needs) of Egyptian coast. The selected location has been Port Safaga (about 50 km South of Hurghada in the Red Sea coast of Egypt), with a DNI of 2496 kWh/m^2 at about 2.5 km from the sea.

The following CSP+D configurations were analyzed from the thermodynamic point of view:

- LT-MED (low temperature multi-effect distillation) unit integrated into a parabolic trough solar power plant (PT-CSP).
- LT-MED-TVC (low temperature multi-effect distillation with thermal vapour compression) unit integrated into a PT-CSP plant, considering steam extractions from the high and low pressure turbine.
- TVC-MED (multi-effect distillation with thermal vapour compression) unit integrated into a PT-CSP plant, considering the extraction from the low pressure turbine.
- RO (reverse osmosis) unit connected to a PT-CSP plant.

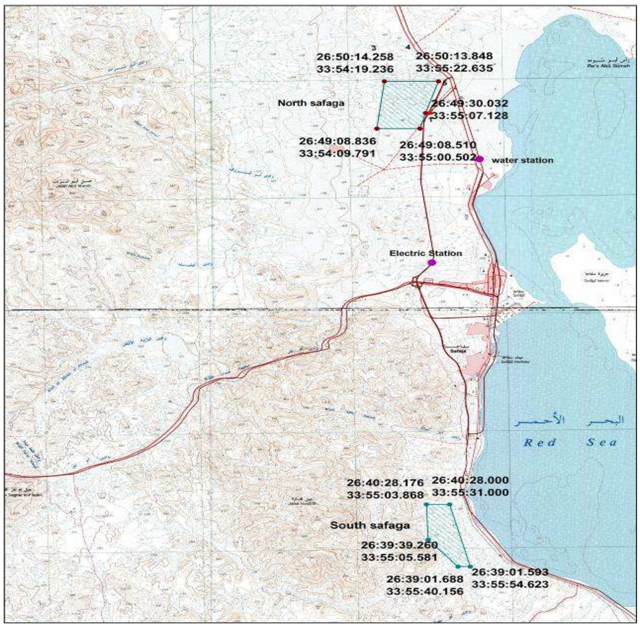

Fig. 8.1. Selected location to carry out the study of combined power and desalination plant in Port Safaga (Egypt)

The same conditions as the power cycle of the commercial plant Andasol 1 have been set. In all studied cases the freshwater and electricity production considered is the same (35,000 m^3/day, 50 MW$_e$, respectively). The results obtained are valid for arid regions, taking a condensing temperature of 58 °C which is suitable for dry cooling as a system of refrigeration in the power cycle.

13 hours molten salts thermal storage system was considered and another hypothesis was that the desalination unit works fully associated with the CSP plant (if this last one is stopped the first one also).

Desalination system	Net output thermal capacity requested (MW$_{th}$)	Overall efficiency (%)	Aperture area (m^2)
LT-MED	161	31.1	733,570
LT-MED-TVC-LP (1.17 bar)	180	27.7	824,040
LT-MED-TVC-HP (18.5 bar)	199	25.2	906,880
RO	175	28.6	756.460
TVC-MED-LP (1.17 bar)	173	28.9	748,830

Table 2. Net output thermal capacity requested, overall CSP+D efficiency and aperture area resulting from each desalination configuration proposed at Port-Safaga location (Egypt), considering 50 MW$_e$ and 35,000 m^3/day of, respectively, power and water net production

The results showed slightly better combined efficiency of CSP-LT-MED against CSP-RO and lower needed solar field (Table 2). However, when the levelized energy and water costs are estimated (Table 3), the differences are very small.

Cogenera-tion system	Investment solar plant (M€)	Investment desalination plant (M€)	LEC (€/kWh)	LWC (€/m^3)
PT-CSP / RO	406.76	29.83	0.178	0.649
PT-CSP / LT-MED	380.38	36.84	0.169	0.706

Table 3. Comparative levelized costs of power (50 MW_e net production) and water (35,000 m^3/day net production) cogeneration with PT-CSP/RO and PT-CSP/LT-MED configuration at Port-Safaga (Egypt)

References:

P. Palenzuela, D.C. Alarcón-Padilla, G. Zaragoza, E. Guillén, M. Ibarra, J. Blanco. Thermodynamic characterization of combined parabolic-trough solar power and desalination plants in Port Safaga (Egypt). In: SolarPACES 2011. Concentrating Solar Power and Chemical Energy Systems. 20-23 September 2011, Granada, Spain.

J. Blanco, P. Palenzuela, D. Alarcón, G. Zaragoza, E. Guillén, M. Ibarra. Assessment of suitable configurations for combined Solar Power and Desalination plants. 2nd European Conference on Polygeneration. Technologies and Perspectives. Tarragona (Spain), 30 Marzo-1 Abril 2011.

CONSOLI+DA – Consortium of Solar Research and Development (M)

M = individual member country task-shared activities of interest to SolarPACES

Contact: Julián Blanco Gálvez, PSA-CIEMAT (julian.blanco@psa.es); Vicente J. Subiela, Instituto Tecnol (julian.blanco@psa.es); Vicente J. Subiela, Instituto Tecnologico Canarias - ITC (vsubiela@itccanarias.org).
Participants: 20 Spanish companies leaded by ABENGOA and 18 Spanish Research Institutions. CIEMAT was subcontracted by ITC.
Funding: 24 M€ from Spanish Ministry of Industry, Commerce and Tourism (INGENIO Program; CENIT Project).
Duration: 2008 – 2011

Background: The general purpose of the project is to lay an R&D infrastructure that consolidates the leading role of Spain in concentrating solar power technologies. As CSP can effectively contribute to the achievement of defined targets in energy policies (at EU level), such the 20% carbon dioxide emission reduction by 2020, the important growing of project development is reasonably expected to occur not only in Spain but also in other countries. Main objective of this project is, therefore, to consolidate the leading position of Spanish companies in the field of concentrating solar power.

Objectives: The Department of Environmental Applications of Solar Energy of PSA-CIEMAT participates in a particular leg of the project which concerns desalination, with the general objective of achieving the effective integration of seawater desalination in concentrated solar power plants. The specific goals of the activity are: (i) to evaluate and select the most feasible options amongst the different technologies both of solar collection and desalination; (ii) to perform technical and economic analysis of the different combined options; and (iii) to analyze in depth those options by carrying out conceptual pre-designs of particular plants.

Achievements in 2011: During the last year of the project, the Department of Environmental Applications of Solar Energy has collaborated during the Phase 2 of the CONSOLI+DA Project. This phase involved the basic engineering of three different solar thermal desalination plants to be installed in three locations of the Canary Islands (Spain).

The first plant is a 50 MW_e parabolic trough solar power plant coupled to a seawater multi-effect (MED) distillation plant with a capacity of 40.000 m^3/day (2 x 20.000 m^3/day units). The outlet steam from the turbine (70 °C) is condensed within the first effect of the MED units driving the thermal desalination process.
The second plant is a 50 MW_e parabolic trough solar power plant coupled to a modular seawater reverse osmosis (RO) plant with a capacity of 30.000 m^3/day (6 x 5.000 m3/day). Third plant is a 100 m^3/day seawater desalination plant based on membrane distillation technology. Due to the current thermal performance of this technology, its use is mainly focused to small fresh water production capacities in isolated areas. The thermal energy required for the process (at 85 °C) is supplied by an evacuated tube solar collector field.

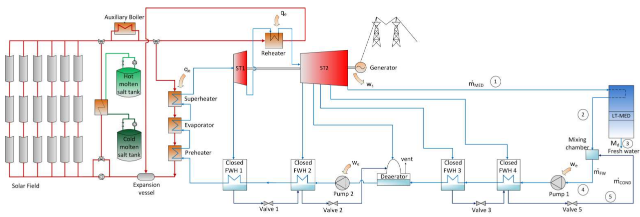

Fig. 8.2. Scheme of Low Temperature Multi-Effect Distillation system coupled to a parabolic trough collector field

References:

P. Palenzuela, D. Alarcón, J. Blanco, E. Guillén, M. Ibarra, G. Zaragoza. Modeling of the heat transfer of a solar multi-effect distillation plant at the Plataforma Solar de Almería. Desalination and Water Treatment, 31, 257-268, 2011.

Palenzuela, P., G. Zaragoza, D. Alarcón and J. Blanco. Simulation and evaluation of the coupling of desalination units to parabolic-trough solar power plants in the Mediterranean region. Desalination, 281, 379-387, 2011.

P. Palenzuela, G. Zaragoza, D. Alarcón, E. Guillén, M. Ibarra, J. Blanco. Assessment of different configurations for combined parabolic-trough (PT) solar power and desalination plants in arid regions. Energy 36 (2011), pp.: 4950-4958.

TEcoAgua – Sustainable Technologies for the Integral Water Cycle (M)

M = individual member country task-shared activities of interest to SolarPACES

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Participants: Leader Abengoa Water. 10 Spanish Companies and 21 subcon-tracted Spanish Research Institutions; CIEMAT was subcontracted by Abengoa Water.
Total Project Budget: 18 M€
Funding: Spanish Ministry of Science and Innovation (INGENIO program CENIT project)
Duration: 2009 – 2012
Background: The general purpose of the project is the development of sustainable technologies for the generation of alternative water resources. In order to achieve this goal, advanced technologies in reclamation of contaminated natural resources, wastewater treatment, new desalination processes, etc., must be investigated.

Objectives of Abengoa Water – CIEMAT collaboration: The Department of Environmental Applications of Solar Energy of PSA-CIEMAT participates in a particular leg of the project which concerns desalination, with the general objective of achieving the effective integration of a solar powered double-effect (LiBr-H_2O) absorption heat pump (DEAHP) with a multi-effect distillation (MED) unit in order to increase the thermal performance of this seawater desalination process. The specific goals of the activity are: (i) Design and implementation of a solar powered DEAHP-MED system; (ii) to perform the experimental assessment of the solar DEAHP-MED plant; (iii) Modeling, and (iv) Preliminary design of pre-commercial systems.

Fig. 8.3. Double-effect (LiBr-H_2O) absorption heat pump coupled to a multi-effect distillation (MED) unit at PSA facilities (Spain)

Achievements in 2011: During this year a 230-m^2 parabolic trough solar field (NEP Polytrough 1200) has been coupled to the PSA DEAHP unit. The solar field works with synthetic oil that is heated up to 220 °C. This oil drives a steam generator that generates the saturated steam (180 °C, 10 bar abs) required by the high temperature generator of the heat pump.

Additional instrumentation has been specified and acquired in order to improve the performance of the simulation models for both the MED and DEAHP units.

7.4.2 Solar Thermal Desalination Systems

MEDIRAS – Membrane Distillation In Remote Areas (M)

T = Task-shared activities by SolarPACES member countries
Contacts:

1) Joachim Koschikowski, (Fraunhofer Institute for Solar Energy, ISE).
2) Vicente J. Subiela (Instituto Tecnológico de Canarias, SA, ITC)

Addresses of contact:

1) joachim.koschikowski@ise.fhg.de
2) vsubiela@itccanarias.org

Participants: 9 UE institutions (universities, R&D centers and private companies) and one Tunisian company
Funding: 3,4 M€ from the European Commission, Call ENERGY.2007.4.1.3: Small distributed systems for seawater desalination
Site: www.mediras.eu
Duration: 2008 – 2011
Background: In many places worldwide, drinkable water is already a scarce good and its lack will rise dramatically in the near future. Industrial-scale desalination plants provide big cities with fresh water but small villages in rural remote areas do not profit from these installations. The high technical complexity of the large plants and the lack or limited access to the electricity grid, complicates the use of standard desalination techniques in these places. In these regions the lack of drinkable water often corresponds with a high solar insulation. This speaks for the use of solar energy as the driving force for water treatment systems. Membrane distillation is a desalination technology that can easily be connected to a solar thermal collectors field, with or without heat storage, and can be driven also by waste heat. The previously operated units (2005 - 2008) have demonstrated the high energy efficiency (See Fig 8.4).

Objectives: Main objective is to initialize a market penetration of small solar thermally driven membrane distillation systems, according to the following goals: 1) Reduction of water production costs; 2) Expansion of field for applications leading to an expanding market and decreasing production costs by serial production; 3) Water quality management leading to a sustainable insurance of the required product water quality according to the application, even under harsh operating conditions; 4) Financing concept for market introduction of MD-systems in regions with low purchasing power (developing countries and emerging nations).

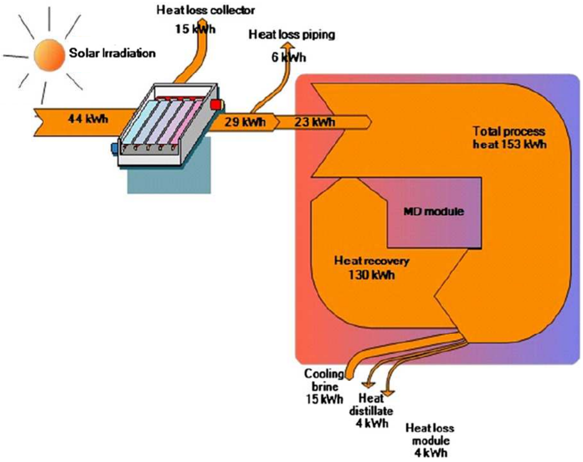

Fig. 8.4. Heat flows and losses on a sunny day in February 2010 (117 l distillate output in 8.2 h operation time)

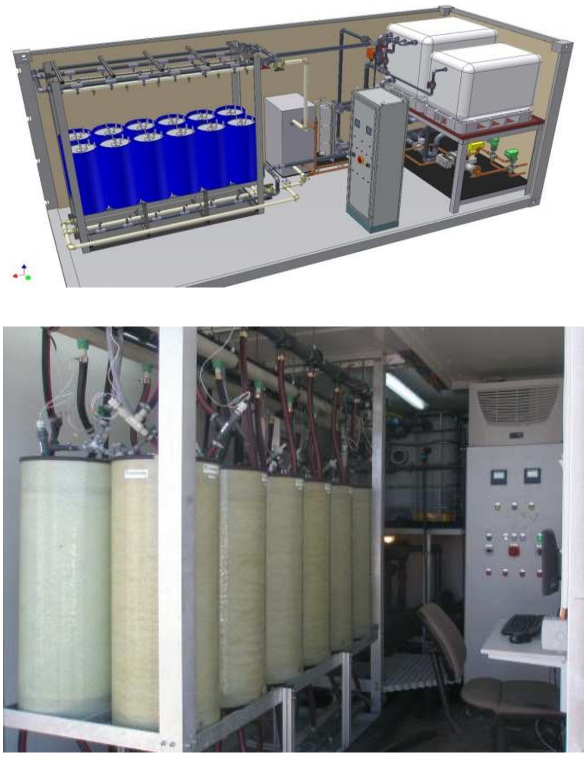

Fig. 8.5. 3D design of the system and installed plant on Gran Canaria island (Spain) (Source: Fraunhofer Institute for Solar Energy Systems, ISE).

Achievements in 2011: Commissioning and operation of five solar MD units: a compact two loop system (300 L/day) in Tenerife Island (Spain), two compact systems in Tunisia (150 L/day) and two multi-module two loop systems: Gran Canaria Island, Spain (3.000 L/day, see Fig 2) and Pantelleria, Italy (5.000 L/day). Development of a post-treatment unit for the distilled water.

References:

Gemma Raluy, Rebecca Schwantes, Vicente J. Subiela, Baltasar Peñate, Gustavo Melián, Juana Rosa Betancort. "Operational experience of a solar membrane distillation demonstration plant in Pozo Izquierdo-Gran Canaria Island (Spain)". Desalination Vol 210 pp 1-13 (2012).

7.4.3 Solar water detoxification and disinfection systems

Development of glass tube coatings for solar photocatalytic water treatment applications – SolPur (M)

M = individual member country task-shared activities of interest to SolarPACES

Contact: Christian Jung, christian.jung@dlr.de
Duration: January 2009- June 2011
Participants: Hirschmann Laborgeräte GmbH & Co. KG (D), Deutsches Zentrum für Luft- und Raumfahrt e.V. (D); KACO new energy GmbH (D)
Funding:513 k€; German Ministry for Education and Research (D)
Background: Titanium dioxide has been utilized in numerous examples to degrade hazardous compounds with solar radiation. Despite the large potential for environmentally benign water treatment, only a few applications and pilot plants have been established so far. One of the drawbacks of titanium dioxide as a photocatalyst for water treatment is its difficult separation from purified water. As residual catalyst concentrations usually cannot be accepted, energy demanding advanced filtration techniques would have to be applied to remove it below acceptable limits. Photocatalytically active coatings offer an interesting alternative to suspensions as they eliminate the energy demanding catalyst separation process. Moreover durable coatings would allow for less pump energy and very simple fluid installations for solar photocatalytic water treatment.

Fig. 8.6. Solar prototype plant for photocatalytic activity tests of coated glass tubes (receiver in the background) and photocatalyst suspensions (receiver in the front) in individual loops

Objectives: In this project, commercially available formulations were applied to build up TiO_2 coatings inside glass tubes as receiver elements for photoreactors. After screening of available products, application conditions were optimized and promising coatings were checked with respect to activity and long term performance. Solar reactors with photocatalytic coatings were evaluated.

Achievements in 2011: A prototype plant was erected for parallel tests with photocatalytically active coated tubes and photocatalyst suspensions under comparable conditions in individual loops. The photocatalytic activity of TiO_2 coated glass tubes was compared with suspended AEROXIDE® TiO_2 P25 (100 mg/L). The activity was checked via the degradation of sulfamethoxazole (1 mg/L) below the detection limit (<10 µg/L, HPLC-DAD) with 150 L in each loop.

The degradation of sulfamethoxazole below the detection limit was achieved with both loops. A lumped first order kinetics evaluation (against the collected global solar energy on the aperture per batch volume) indicates about 10 times faster degradation with the suspended photocatalyst.

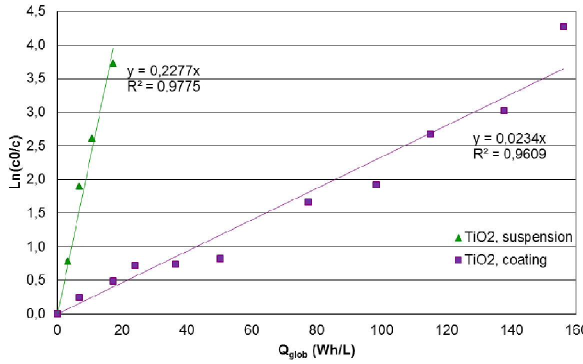

Fig. 8.7. Degradation of sulfamethoxazole under solar insulation with suspended and coated TiO_2

The results indicate that solar water treatment with TiO_2 coatings on glass tubes is possible at a prototype scale. While the separation of the photocatalyst from the purified water was avoided, the specific activity of the coated receiver reactor has to be enhanced by further measures in order to achieve attractive treatment systems in the future based on TiO_2 coatings.

Treatment and Reuse of Waste Waters for Sustainable Management – TRAGUA (M)

M = individual member country task-shared activities of interest to SolarPACES

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Duration: September 2006 – June 2012
Participants: Up to 24 Spanish Public Institutions and Companies.
Funding: Spanish Ministry of Education and Science (National R&D Programme): 4,900 k€.
Background: Spain is the European country with the highest water deficit and only 5% of waste water is reused. The reasons for the small water reuse are diverse, the most important among them being the lack of treatment protocols for treated waters coming from Municipal Wastewater Treatment Plants (MWTP) and the lack of clear criteria for choosing technologies.

Purpose: A five-year project (2006-2011) extended for a further 9 months (until June 2012) for enhancing wastewater reuse in Spain. When finished, the Program will provide with an inventory of waste waters for potential reuse, treatment protocols according to their characteristics and the available economically improved technologies, standard methods of chemical, microbiological and toxicological analysis, information about the water impact on the environment and the respective socio-economic analysis.

Achievements in 2011: As normal municipal wastewater treatment plants (MWTP) are not able to entirely degrade xenobiotic substances (XS), the study has focused on modified solar photo-Fenton treatment (5 mg L^{-1} Fe, initial pH 7) of a municipal wastewater treatment plant (MWTP) effluent. However, effluents do not contain compounds which could form photoactive Fe^{3+} complexes. The use of ferrioxalate, humic substances (HA) and mixing the MWTP effluent with small amounts of influent could be justified to form photoactive Fe^{3+} complexes. All experiments were done in MWTP effluent spiked (5 or 100 µg/L) with 15 emerging contaminants (ECs) using a pilot compound parabolic collector (CPC) solar plant designed for solar photocatalytic applications.

The 15 compounds selected were: Acetaminophen, Antipyrine, Atrazine, Caffeine, Carbamazepine, Diclofenac, Flumequine, Hydroxybiphenyl, Ibuprofen, Isoproturon, Ketorolac, Ofloxacin, Progesterone, Sulfamethoxazole and Triclosan. This study focuses on modified solar photo-Fenton treatment (pH □ 7) of an MWTP effluent in which the pH is far from the optimum of 2.8 for photo-Fenton treatment. At this pH, there is still no precipitation and the dominant iron species in solution is $[Fe(OH)]^{2+}$, the most photoactive ferric iron-water complex. A pH far from 2.8 is detrimental to the process, as the concentration of $[Fe(OH)]^{2+}$ is low, thereby justifying the use of oxalic acid, humic acid or a mixture of secondary MWTP effluents with influent wastewater, which could compensate for the disadvantage of the lack of $[Fe(OH)]^{2+}$ by forming ferric iron complexes. The oxalate-enhanced process provided satisfactory degradation results, which were complete within a reasonable time. The only drawback of this process is the low residual pH of the treated water, which must be raised again to at least 6.5 for reuse. XS degradation with the HA-enhanced process was fast and nearly complete.

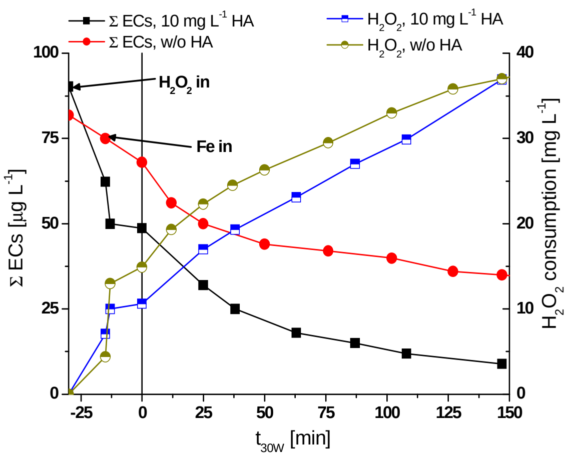

Fig. 8.8. XS (5 µgL^{-1} of each) degradation in real waste water at pH = 6.5, 5 mg L^{-1} Fe and H_2O_2 peroxide consumption with 10 mg L^{-1} HA (■) and without HA (●).

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Integration of solar photocatalytic and biological treatment processes for the removal of emergent contaminants from wastewaters – EDARSOL (M)

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Participants: Plataforma Solar de Almeria. Group of Advanced Oxidation Processes, Univ, Polytech. Valencia, Dept. of Chemical Engineering, Univ. Extremadura.
Funding: Spanish Ministry of Education and Science (National R&D Programme): 0,8 k€.
Background: Although there is available information about the possibility to treat contaminants by different technologies, it is also well-known that non-biodegradable substances, such as pesticides, pharmaceuticals, hormones, synthetic fragrances, and others escape conventional wastewater treatment. Consequently, the application of more exhaustive wastewater treatment protocols, including the use of new and improved technologies, is a necessary task. Moreover, it is also necessary to develop the combination of different advanced chemical and biological techniques for permitting the elimination of recalcitrant compounds.

Purpose: The overall objective will be to design, to build up and to evaluate treatment systems (pilot plants) integrating biological reactors coupled with solar photocatalysis for wastewater treatment containing recalcitrant contaminants, permitting water reuse for irrigation, industry or leisure purposes (according to Spanish Directive RD 1620/2007).

Achievements in 2011: Nowadays the potential of photo-Fenton process for decontamination of biologically persistent wastewater is widely recognized. In this process, hydrogen peroxide consumption could be considered as one of the factors that considerably affects costs. This highlights that an automatically hydrogen peroxide dosing system to keep the concentration optimized throughout the process would be a valuable tool for industrial wastewater remediation plants. Automatic H_2O_2 dosing during photo-Fenton would require a precise online measuring device. Today, several expensive, unreliable and overly-complicated wastewater hydrogen peroxide probes are commercially available. This study focuses on considering dissolved oxygen concentration (DO) as a reaction stage indicator related to H_2O_2 concentration and consumption during photo-Fenton wastewater treatment.

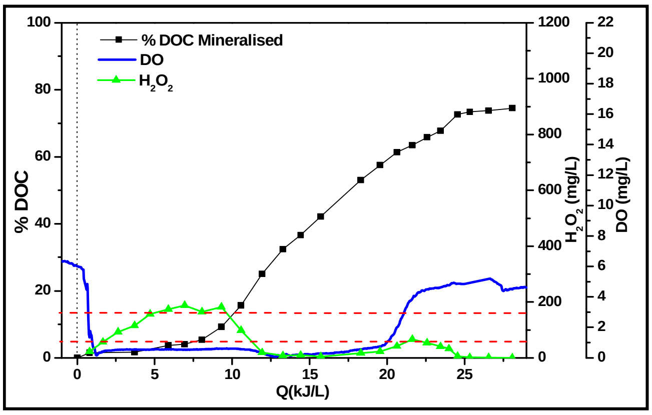

Fig. 8.9. Percentage of DOC mineralized, H_2O_2 and DO concentrations during photo-Fenton (DO set points at 1-3 mg/L, dashed red line).

The results obtained demonstrated the potential for making use of the DO profile for monitoring photo-Fenton, automatically dosing H_2O_2 and determining the end point of the treatment. Results confirmed the inherent relationship between H_2O_2 and DO during photo-Fenton treatment. Therefore, the potential for making use of the DO profile for monitoring photo-Fenton, automatically dosing H_2O_2 and determining the end point of the treatment was demonstrated.

Another part of the work has been to use LC-TOF-MS techniques to increase the knowledge of the behaviour of contaminants and its main TPs during solar photo-Fenton treatment and the possibility of combination with biological treatment for the regeneration of effluents. It has been demonstrated that the composition of the water does not substantially affect the type of compounds identified, but it does affect their relative abundance during the process. Furthermore, experiments in saline water containing high concentrations of chloride ions revealed the possible formation of chlorinated by-products during treatment of water that disappeared at the end. Thus, analytical assessment of wastewater treatments, including identification and monitoring of the TPs generated becomes fundamental in order to better understand the mechanisms governing degradation, for viable optimization of treatments and to guarantee the quality of the treated water.

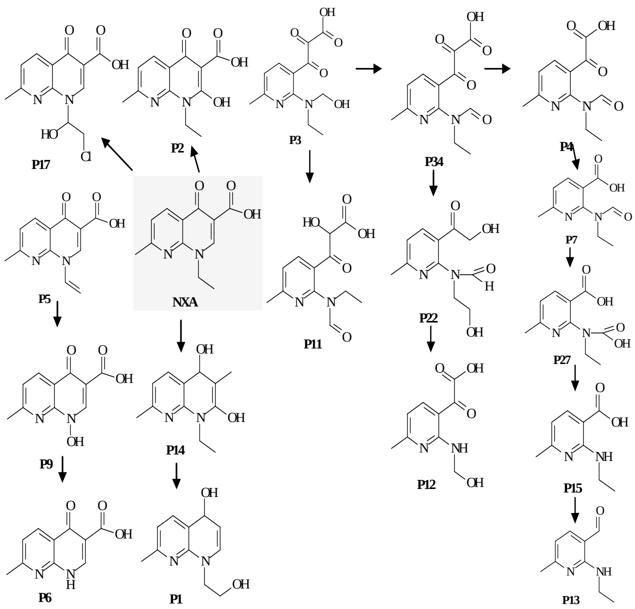

Fig.8.10. Proposed photo-Fenton Nalidixic acid degradation pathway in wastewater containing NaCl.

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Development of new treatment schemes based on solar photocatalysis for wastewater reclamation – FOTOREG (M)

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Participants: Plataforma Solar de Almeria (PSA). Univ. Almería.
Funding: Spanish Ministry of Education and Science (National R&D Programme): 0,6 k€.
Background: The reuse of wastewater requires physical and chemical treatments that provide water the minimum quality required for its intended use. There are currently technologies that achieve these goals, with different costs and that result problematic in terms of ~~its~~ their implementation,. This highlights the need to expand on the available technologies with the view to minimizing energy costs and environmental risks. Additionally sophisticated analytical techniques are needed in order to ensure the assessment quality of the reclaimed water treatments. These techniques include the study of the potential risk of the use of treated water.

Purpose: The objective of the project is to explore new sustainable strategies based on the use of solar energy, for the regeneration of wastewater in order to reuse for agricultural, industrial or recreational purposes. In this sense, attention should be given both to the disinfection of the treated water from secondary processes (biological, activated sludge), and to the elimination of recalcitrant pollutants that remain in the cycle of water reuse and accumulate in the environment.

Fig. 8.11. Experimental installations at PSA used to the development of experimental activities of FOTOREG project

Achievements in 2011: The objective has been to evaluate the durability and photocatalytic activity of supported TiO_2 on glass spheres using as a test reaction the decomposition of dichloroacetic acid and acetaminophen. The TiO_2 photocatalyst was prepared by sol-gel technique the glass spheres were covered with sol by dip-coating and dried. Experiments have been performed using two different reactors. The first one was conducted in a beaker, in order to evaluate the behavior of Dichloracetic acid under treatment with spheres-TiO_2. The second reactor was a glass tube, similar to the ones used in a solar CPC pilot plant. The same amount of catalyst was used for all of the experiments. The first experiments showed photocatalytic activity using TiO_2 supported on glass spheres, and confirm the evidence that the degradation can be performed under solar light.

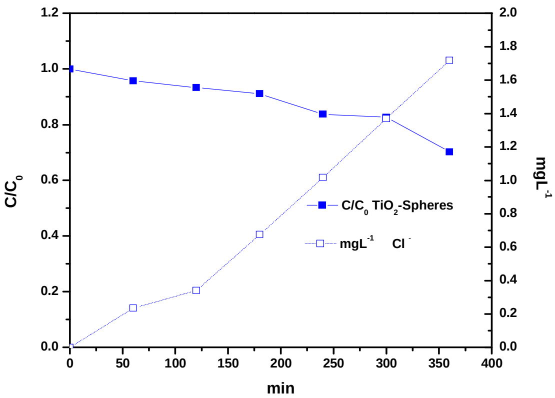

Fig. 8.12. Dichloracetic acid degradation and evolution of chlorides during photocatalytic treatment with TiO_2 supported on glass spheres in a rector tube of CPC.

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