International Energy Agency (IEA)

Solar Power and Chemical Energy Systems

SolarPACES

Annual Report

2010

Edited by C. Richter
in cooperation with
J. Blanco, P. Heller, M. Mehos
A. Meier, R. Meyer

DLR

Deutsches Zentrum für Luft- und Raumfahrt e.V.

Cover picture:
Part of the 1.5 MW Maricopa Dish Stirling Plant at Peoria, Arizona. (Photo Courtesy SES)

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Deutsches Zentrum für Luft- und Raumfahrt e.V.
Köln/Germany

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.

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Foreword

June 2010

Hello All,

The 2010 Annual Report comes to you at a very busy time for SolarPACES, as following the IEA procedures, we are now finishing our current 2007-2011 five-year term and preparing for the next one. The past term has witnessed impressive worldwide dynamic growth of CSP plants led by Spain and the US, and rapid parallel growth in SolarPACES membership, from 12 to 20 member countries. This increased strength helped reinforce our worldwide dissemination activities, most visibly in this year's 17th SolarPACES Symposium, which is expected to have an attendance of nearly 1000. We are very pleased to see how this traditional event has grown in response to the increasing need for an independent platform where experts from R&D, industry, policy and financing can meet. Maintaining and increasing the impact and quality of the SolarPACES Symposium will be one of the high priority tasks in the upcoming five-year term starting in 2012.

Global power supply has risen significantly in the political agenda of many countries as a consequence of the tragic Fukushima accident last March. Renewable Energies in general had already achieved a significant share in the overall energy mix in many countries, and this trend seems to have received stronger political support since then. As the shares of fluctuating renewable sources increase, the ability of each technology to match demand is of growing importance, and concentrating solar technologies, with their specific potential to provide short-term (thermal/power) and long-term chemical storage, have a lot to contribute to the optimal integration of the largest renewable source of clean, sustainable and affordable energy still to be tapped, the sun. Against this background in the coming term, an even stronger SolarPACES will focus on the internationally coordinated development and deployment of concentrating solar technologies to further reduce cost, increase dispatchability, and reinforce awareness of the benefits of CST.

While we are still heading in the same direction, personal changes are sometimes unavoidable. We want to express our most heartfelt gratitude to our former Chairman, Dr. Thomas Mancini of Sandia National Laboratories, who resigned as Chairman in April 2011, after serving SolarPACES for seven years in this capacity (and many more years as Operating Agent). We are all indebted to Tom Mancini's dedicated effort to the progress and development of the SolarPACES Implementing Agreement. The growing SolarPACES community will stay in close touch and wishes him a sunny retirement.

As we are now looking forward to the election of a new Chairman in the autumn ExCo Meeting, we would also like to express our gratitude to the continuing Operating Agents and ExCo Members of SolarPACES for their dedication to our common goals, and hope to keep on working with this great team in the future.

Robert Pitz-Paal
Acting Chair

Christoph Richter
Executive Secretary

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List of Acronyms

A	Austria
ACC	Air-cooled condenser
AEE	Arbeitsgemeinschaft Erneuerbare Energie (A)
AF	annular flow
ALG	Algeria
ANR	National Research Agency (F)
ANU	Australian National University (AUS)
AOD	aerosol optical data
AOP	advanced oxidation process
ASES	American Solar Energy Society
ASI	Australian Solar Institute
ASIC	Austria Solar Innovation Center
ASME	American Society of Mechanical Engineers
AUS	Australia
AZ	Arizona (USA)
B	Belgium
BfE	Swiss Federal Office of Energy (CH)
BGU	Ben Gurion Univ. of the Negev (IL)
BMU	Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (D)
BMVIT	Federal Ministry for Transport, Innovation and Technology (A)
BMZ	Federal Ministry for Technical Cooperation and Development (D)
BRA	Brazil
CAS	Chinese Academy of Sciences
CB	carbon black
CCD	charge coupled device
CEA	Commissariat à l'Energie Atomique (F)
CENER	Centro Nacional de Energías Renovables (E)
CENIM	Centro Nacional de Investigaciones Metalúrgicas (E)
CERTH	Centre for Research & Technology Hellas (GR)
CESI	Centro Elettrotecnico Sperimentale Italiano
CFE	Comisión Federal de Electricidad (MEX)
CH	Switzerland
CIDAUT	Centro de Investigación y Desarrollo en Automoción (E)
CIE	Energy Research Centre, UNAM (MEX)
CIEMAT	Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (E)
CLFR	compact linear Fresnel reflector
CNR	Consiglio Nazionale delle Ricerche (I)
CNRS	Centre National de la Recherche Scientifique (F)
COC	cycles of concentration
CONACYT	Centro Nacional de Ciencia y Tecnología (MEX)
CPC	compound parabolic collector
CPERI	Chemical Process Engineering Researc Institute, CERTH (GR)
CREED	Centre de Recherches sur l'Environnement l'Energie et les Déchets (F)
CRES	Centre for Renewable Energy Sources (GR)
CRS	central receiver system
CSIC	Consejo Superior de Investiación Científica (E)
CSIRO	Commonwealth Scientific and Research Organisation (AUS)
CSP	concentrating solar power
CST	concentrating solar technologies
CTI	Commission for Technology and Innovation (CH)

D	Germany
DEM	digital elevation model
DG RTD	Directorate General Research (EC)
DG TREN	Directorate General Transport and Energy (EC)
DII	Desertec Industrial Initiative
DIN	Deutsches Institut für Normung (D)
DISS	Direct Solar Steam
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V. (D)
DNI	direct normal irradiation
DOE	Department of Energy (USA)
DSG	direct steam generation

E	Spain
EC	European Commission
ECMWF	European Centre for Medium-Range Weather Forecasts
EdM	Paris School of Mines (France)
EERA	European Research Alliance
EGY	Egypt
EHF	Univ. Of Oldenburg (D)
EIT	European Institute of Technology ()
ENEA	Agency for New Technology, Energy and Environment (I)
ENEL	Ente Nazionale per l'Energia eLettrica (I)
ENTPE	École Nationale des Travaux Publics de l'État (F)
ESI	School of Engineering, Univ. Seville (E)
ESKOM	Electricity Supply Commission (ZA)
ESRI	Environmental Systems Research Institute (USA)
ESTELA	European Solar Thermal Electricity Association
ESTIA	European Solar Thermal Industry Association
ETH	Institute of Energy Technology (CH)
ETP	Energy Technology Perspectives
EU	European Union
EUMENA	Europe, North Africa and the Middle East
ExCo	Executive Committee (SolarPACES)

F	France
FAMP	flash-assisted multi-wavelength pyrometry –
Fhg-ISE	Fraunhofer-Institut für Solare Energiesysteme in Freiburg (D)
FIFA	International Federation of Association Football
FP6, FP7	6th, 7th Framework Programme (EC DG RTD)

GEBA	Global Energy Balance Archive
GHG	greenhouse gas
GHI	global horizontal irradiance
GIS	Geographic information system
GR	Greece

HCE	heat collection element (parabolic trough)
HI	Hydrogen-Iodide
HPLC-UV	High-Performance Liquid Chromatography with UV Detector:
HVDC	High Voltage Direct Current
HyS	Hybrid sulfur cycle

I	Italy
IBR	Immobilized bed reactor
IEA	International Energy Agency
IEM	Immunologie et Embryologie Moléculaires CNRS (F)
IEW	International Energy Workshop
IF	intercept factor
IIE	Instituto de Investigaciones Eléctricas (MEX)
IL	Israel

IMDEA	Instituto Madrileño de Estudios Avanzados (E)
INCO	International Cooperation Programme (EC)
INESC-ID	Instituto de Engenharia de Sistemas e Computadores Investigação e Desenvolvimento (P)
INETI	Instituto Nacional de Engenharia, Tecnologia e Inovação (P)
IR	infrared
IR	Ireland
ISCC	integrated solar combined-cycle
ISE	Institut für Solare Energiesysteme
ISES	International Solar Energy Society
ISO	International Standard Organization
ITC	Instituto Tecnológico de Canarias (E)
ITD	initial temperature differential

J	Japan
JOR	Jordan
JRC	Joint Research Centre (EC)

KAUST	King Abdullah University of Science and Technology
KEN	Kenya
KIC	Knowledge and Innovation Communities
KIER	Korea Institute of Energy Research
KJC	Kramer Junction Company (USA)
KOR	Korea
KSA	Kingdom of Saudi Arabia
KSI	Kolmogorov-Smirnoff Integral

LASH	Laboratoire des Sciences de l'Habitat (F)
LC-MS-TOF	liquid chromatography-mass spectrometry-time-of-flight
LCA	life cycle assessments
LCC	life cycle costs
LCOE	levelized cost of electricity
LFC	Linear Fresnel Collector
LFR	linear Fresnel reflector
LT-MED	low temperature mult-effect distillation
LT-MED-TVC	low temperature multi-effect distillation with thermal vapour compression

MB	mean bias
MC	Monte Carlo
MD	Membrane distillation
ME	Meteosat East
MENA	Middle East and North Africa
MEX	Mexico
MF	manganese-ferrite
MFG	Meteosat first generation satellite
MP	Meteosat Prime satellite
MPSZ	MgO partially-stabilized Zirconia
MSG	Meteosat second generation satellite
MWSF	Megawatt Solar Furnace, CNRS-PROMES (F)
MWTP	municipal wastewater treatment plants

NASA	National Aeronautical and Space Administration
NASA LaRC	Langley Research Center (USA)
NC	National Coordinator (Task 2)
NEAL	New Energy Algeria
NG	natural gas
NL	Netherlands
NM	New Mexico (USA)
NREA	National Renewable Energy Agency (EGY)

NREL	National Renewable Energies Laboratory (USA)
NSF	National Science Foundation (USA)
NSO	Nevada Solar One (USA)
NTUA	National Technical University of Athens (GR)
NV	Nevada (USA)
NWU	North West University (ZA)

OA	Operating Agent (SolarPACES)

P	Portugal
PCM	phase change materials
PDVSA	Petróleos de Venezuela, S.A.
PET	polyethylene terephthalate
PG&E	Pacific Gas & Electric
POL	Poland
PROMES	Laboratoire Procédés, Matériaux et Energie Solaire, CNRS (F)
PSA	Plataforma Solar de Almería (E)
PSI	Paul Scherrer Institute (CH)
PT-CSP	Parabolic trough-concentrating solar power
PV	Photovoltaic
PVPS	Photovoltaic Power Systems Agreement (IEA)

RCH	Chile
REWP	Renewable Energy Working Party (IEA)
RMSD	Root Mean Square Deviation
RO	(reverse osmosis)
RPC	reticulate porous ceramic foam ()

S	Sweden
SAI	Solar America Initiative
SBP	Schlaich Bergermann und Partner (D)
SCADA	Supervision, control and data acquisition
SCC	solar-driven combined cycle
SCE	Southern California Edison (USA)
SD	standard deviation
SEGS	Solar Electric Generating Systems
SEIA	Solar Energy Industries Association (USA)
SES	Stirling Energy Systems, Inc.
SFERA	Solar Facilities for the European Research Area (EU)
SHC	Solar Heating and Cooling Implementing Agreement (IEA)
SI	sulfur-iodine cycle
SNF	Schweizerische Nationalfonds (Swiss National Science Foundation) (CH)
SNL	Sandia National Laboratories (USA)
SODIS	Solar Water Disinfection
SolarPACES	Solar Power and Chemical Energy Systems (IEA)
SPG	Steiner-Prematechnik-Gastec GmbH (Solutions for Petroleum and Gas (D)
SRB	Serbia
SSPS	Small Solar Power Systems (IEA)
START	Solar Thermal Analysis, Review and Training (SolarPACES)
STC	standard test conditions
STEII	Solar Thermal Electricity European Industrial Initiative
SUNY	State Univ. of New York

TOD	time of delivery
TMY	Typical MeteorologicalYear
TUN	Tunisia

UAE	United Arab Emirates
UC	Univ. Colorado (USA)
UK	United Kingdom

UNAM	Universidad Nacional Autónoma de México
UNEP............	United Nations Environment Program
UNIGE..........	Univ. Genève (CH)
USA	United States of America
USACH.........	Univ. Santiago de Chile
USD	United States Dollar
UV	ultraviolet
WEO	World Energy Outlook
WIS...............	Weizman Institute of Science (IL)
WWTP..........	wastewater treatment plant
XRD..............	X-ray diffraction analysis
ZA.................	Republic of South Africa

1 Report of the SolarPACES Executive Committee for 2010

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 2010, is submitted to the IEA by the SolarPACES Executive Committee.

Part 2 briefly summarizes some recent studies in optimization of CSP plant cooling, especially with respect to water consumption, a topic of growing importance as growing numbers of projects are deployed and need to adapt to restricted water resources at many sites.

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 2010 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 2010 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.

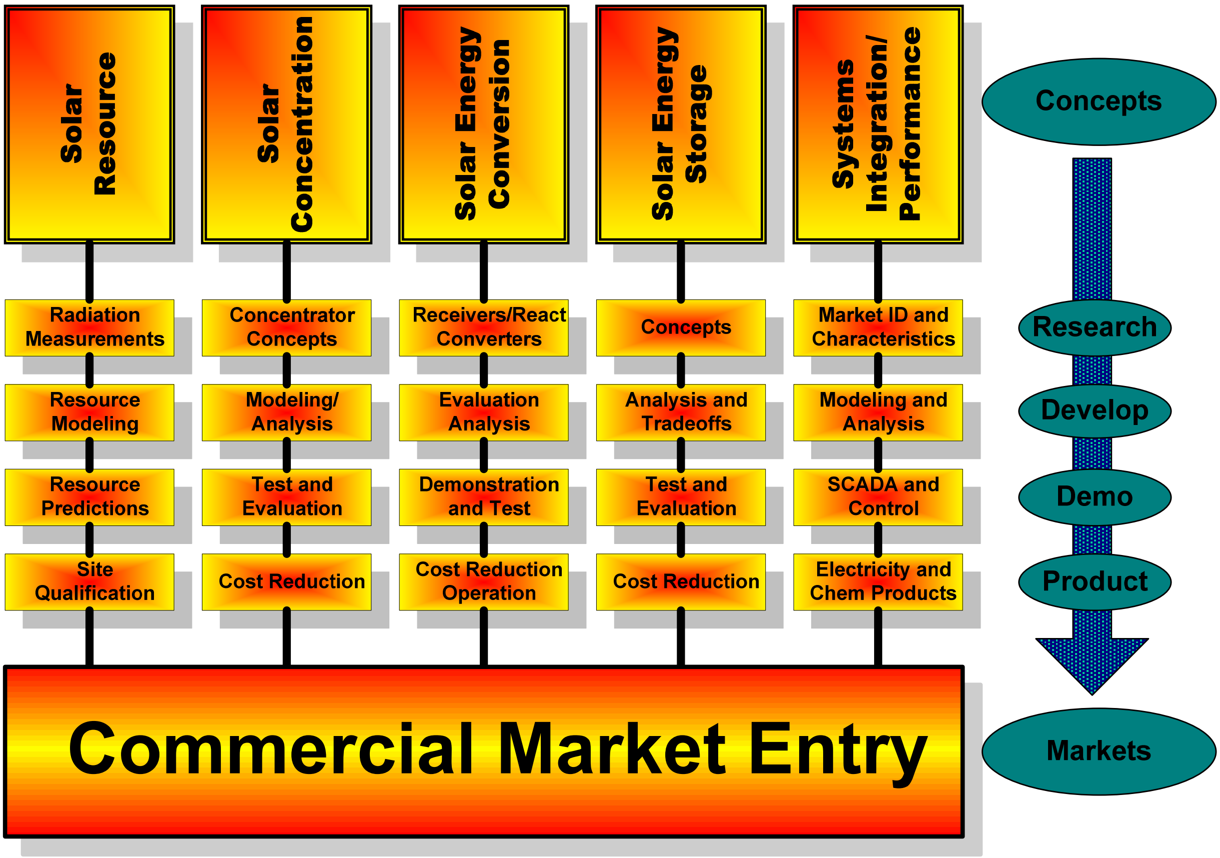

Figure 1.1. Scope of CSP research, development and demonstration work

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

As of July 2011, 18 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. In the past reporting period, Brazil, Mitsubishi and China joint as new members, and membership of Morocco is in progress.

Table 1.1. SolarPACES Membership and Task participation

SolarPACES Membership as of July 2011										
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
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	
Util: Electric Utility; Grey Box: Operating Agent of Task										

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 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 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 Germany, 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

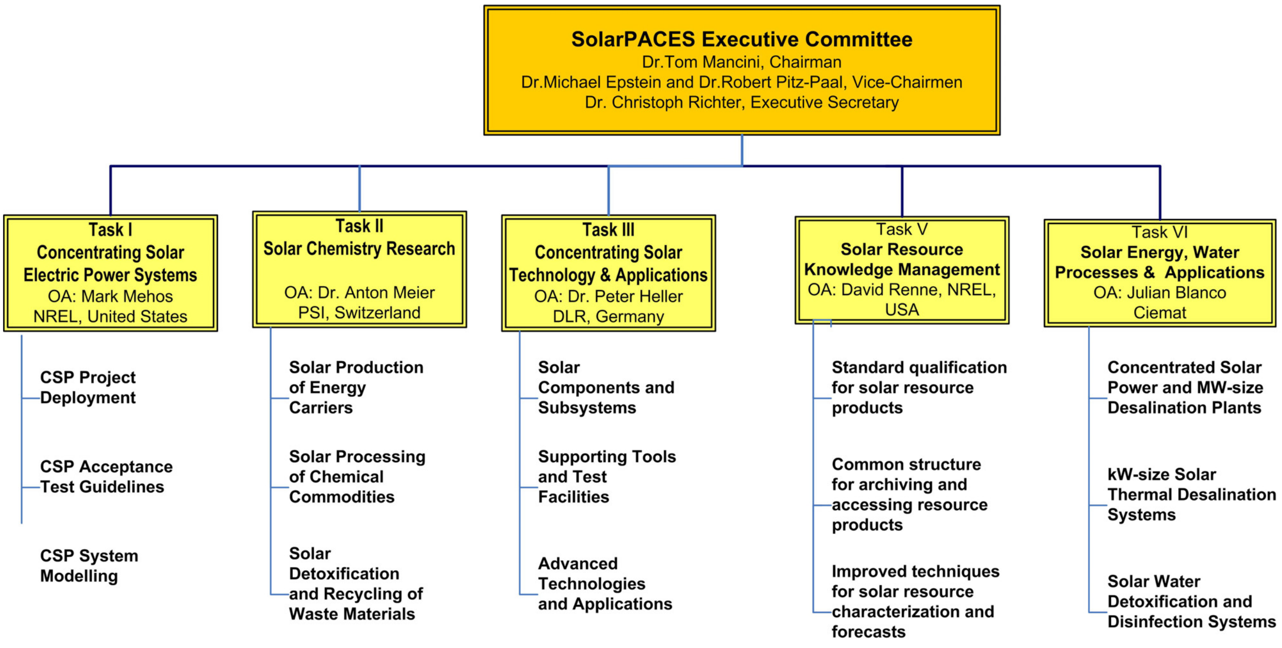

Figure 1.2. Organization of Work within the SolarPACES Task Structure

SolarPACES partners.

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 **16th Symposium**, held from September 21st – 24th 2010 in Perpignan, France, confirmed with more than 800 participants, including a growing share of participants from industry, the dynamic growth in participation seen in the other recent Symposia, and confirmed also the decision to switch the schedule to an annual event. Table 1.2 shows the participation from 42 countries.

Table 1.2. Participation from 42 countries.

Algeria	2	**Netherlands**	3
Australia	17	**Nigeria**	1
Austria	9	**Norway**	3
Belgium	12	**Portugal**	1
Brazil	2	**Qatar**	1
Cameroon	1	**République de Djibout**	1
Canada	2	**Russia**	1
Chile	2	**Saudi Arabia**	3
China	9	**Slovakia**	2
Egypt	1	**South Africa**	10
France	133	**South Korea**	5
Germany	168	**Spain**	142
Greece	4	**Sweden**	4
India	5	**Switzerland**	22
Israel	19	**taiwan**	1
Italy	35	**The Netherlands**	6
Japan	28	**Tunisia**	2
Korea	6	**Turkey**	2
Libya	3	**UAE**	5
Luxembourg	1	**UK**	17
Mexico	7	**USA**	107

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 2009*** was published and distributed among the SolarPACES members and the participants of the 16th 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).

The ***SolarPACES website*** at **www.solarpaces.org** has been redesigned during 2009 and increased the access and download capacity. It has now monthly around 50000 visitors and several hundred downloads of the recent publications.. For the internal use of SolarPACES members, a sharepoint site was installed to increase the possibilities for online cooperation.

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 significants 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 2010 Technology Innovation Award was given to the team of Wolfgang Schiel, Axel Schweitzer, Brian Hunt and Olaf Kracht from SBP for the lead of development and optimization of the Eurotrough/Skal ET parabolic trough collector technology.

Figure 1.3. 2010 Technology Innovation Award winner Wolfgang Schiel (SBP)

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 2010 Lifetime Award winners in recognition of their decades-long contributions to the development of CSP technology are Prof. Valeriano Ruiz Hernandez, Chair of Thermodynamics at School of Engineeering (ESI) Univ. Seville and Arnold Goldman, Chairman of Brightsource Energy.

Figure 1.4. Lifetime Award Winners Prof. Valeriano Ruiz (left) and Arnold Goldman

1.7 *Meetings and Presentations in 2010*

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	Presentation “SolarPACES: International Cooperation in CSP R&D” ESTELA Solar Thermal Industry Forum, Seville, Spain
March	
15th-16th	Participation IEA Spring Workshop Renewable Energy
17th	Participation 56th REWP Meeting
April	
9th	Presentation “SolarPACES: International Cooperation in CSP R&D” CSP Workshop Green Expo, Daegu, South Korea
13th - 14th	78th SolarPACES ExCo Meeting, Seogwipo, Jeju, South Korea
15th	ExCo Host Country Day
24th	IEA Workshop WEO 2010 preparation, Renewable Energy Section
June	
7th	Chairing of CSP session at Renewable Energy World Europe Conference, Amsterdam
September	
7th	IEA Energy Technology Network Communication Seminar/Workshop
9th	Presentations “Global CSP potential up to 2050” and “Established and Emerging Markets:USA, India, China” at Zeroemission Conference, Rome, Italy
19th	79th ExCo Meeting, Perpignan, France
20th	Task I Meeting Task II Meeting Task III Meeting Task VI Meeting
21st - 24th	16th SolarPACES Conferrence, Perpignan, France

2. Cooling of CSP Plants

Today's solar thermal power plants are similar in design to conventional power plants and normally use wet cooling towers to achieve maximum performance. The associated water consumption poses severe constraints for deployment in the typically arid target regions. Several recent studies have analyzed the impact and possible optimization strategies. This chapter briefly summarizes some results.

2.1 Water Consumption in Parabolic Trough Plants

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Michael J. Wagner, michael.wagner@nrel.gov
Charles Kutscher, chuck.kutscher@nrel.gov

Duration: 2009 – 2010

Participants: National Renewable Energy Laboratory (USA), WorleyParsons Group, LLC (USA).

Funding: Estimated $250k funded by US Department of Energy through NREL

Background: Water consumption for electric power generation is undergoing increasing scrutiny, with more emphasis being placed on low-water-use technologies. In 2009-2010, the National Renewable Energy Laboratory (NREL), working with WorleyParsons Group, Inc., examined the efficiency and impact of dry and hybrid cooling systems on a nominal 100-MW parabolic trough plant. The studies analyzed different design cases spanning four different U.S. locations: Daggett, California; Las Vegas, Nevada; Phoenix, Arizona, and Alamosa, Colorado.

Objectives: The main objective of this project is to quantify the amount of water consumed at parabolic trough CSP plants and determine the impact on revenue and levelized cost of electricity (LCOE) if one switches to hybrid or dry cooling. The affect of climate and time-of-delivery (TOD) market prices are explored. In the U.S., the highest TOD rates typically correspond to hot summer afternoons, which coincide with the worst cooling performance from a dry-cooled system. Note: Dry cooling and air cooling are used synonymously in this study.

Achievements: The heat rejection system in a CSP plant can take several forms. Traditionally, wet cooling has been used since it provides a heat rejection reservoir at the wet-bulb temperature. However, this mechanism consumes a large amount of water via evaporation, so wet cooling is untenable in locations where the water supply is limited. A traditional alternative to wet cooling is air cooling. This configuration is constrained by the warmer ambient dry-bulb temperature and the large temperature rise in the air stream due to the low specific heat capacity of air. Consequently, in an air-cooled system the negative impact on plant performance is accentuated during the hot summer afternoon hours when both peak electricity demand and opportunity for plant revenue are highest.

The primary design metric for an air-cooled condenser (ACC) is the initial temperature differential or ITD, defined as the difference between the dry-bulb temperature and the condensing steam temperature. In the subject work, WorleyParsons examined different ACC ITD design points to determine the optimum balance between plant capital cost and efficiency for Las Vegas and Alamosa sites. The ITD analysis assumed a dry-cooled plant with a fixed solar field size operating at the selected design-point dry-bulb temperature. To select an optimum ITD for the Las Vegas site, GateCycle™ performance models were run at the design conditions, varying the ITD from 3°C to 22°C. The net plant power from each run took into account the varying ACC fan power loads and steam turbine outputs. The total installed plant cost was adjusted for the different sizes of ACCs as defined by the ITD. The total plant cost and the plant cost per net kW are plotted as a function of the ACC ITD in Figure 2.1 below.

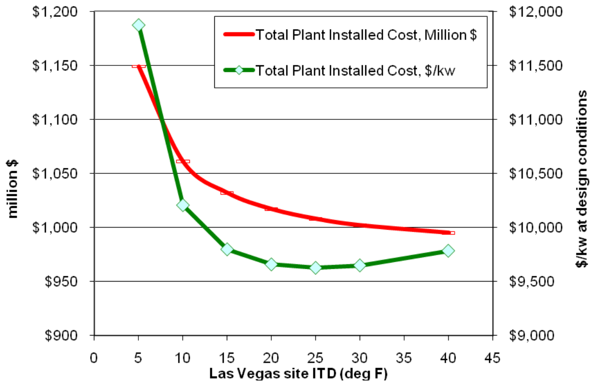

Figure 2.1. Plant Installed Cost per kW capacity can be minimized by proper selection of ACC size.

Total plant installed cost drops with ITD because a larger ITD leads to a smaller and less expensive ACC. However, ITD also affects plant efficiency and design-point capacity. The lowest cost per kW (net) at the design conditions was obtained using an ITD of 25°F (14°C), and this ITD was used in the Las Vegas cooling study. A similar analysis was performed for the Alamosa, Colorado site. For this case the cost per kW was level from 20°F to 30°F ITD. The average was selected, which conveniently aligned with the 25°F ITD (14°C) chosen for the Las Vegas site. These ITDs are considerably lower than what would typically be used for a fossil plant. The lower ITD and commensurately larger ACC can be justified because trough plants operate at a lower steam temperature and are thus more sensitive to the heat rejection temperature. In addition, for an equivalent power output, it is more cost effective to invest in a larger ACC than a larger solar field.

For a specified ITD, one can calculate the temperature and pressure that will be achieved in the condenser at design-point conditions. Due to the lower design-point dry-bulb temperature in Alamosa, Colorado, a 14°C ITD resulted in a 0.088 bar steam turbine backpressure compared to a design turbine exhaust pressure of 0.180 bar in the Las Vegas study. The lowest steam turbine backpressure that can be reasonably achieved with an ACC is about 0.07 bar. Thus, the Colorado site's 100%-dry design approaches this limit, and there is no advantage to selecting a smaller ITD.

The ITDs selected above were optimized based on the design-point ambient temperature. Since this temperature is achieved only during a few of the hottest hours of the year, this method may not produce a system with an optimal LCOE. For this reason, WorleyParsons performed a parametric study based on the cost per MWh produced as opposed to cost per kW capacity. That analysis found broad minima for ITDs from 14°C to 18°C. Thus, in this analysis, an ITD on the order of 14 to 18°C provided the best economics. The optimum ITD for an air-cooled plant depends on multiple parameters including weather patterns, solar field cost, ACC cost, and market time-of-delivery prices. An optimization study should be performed for each project.

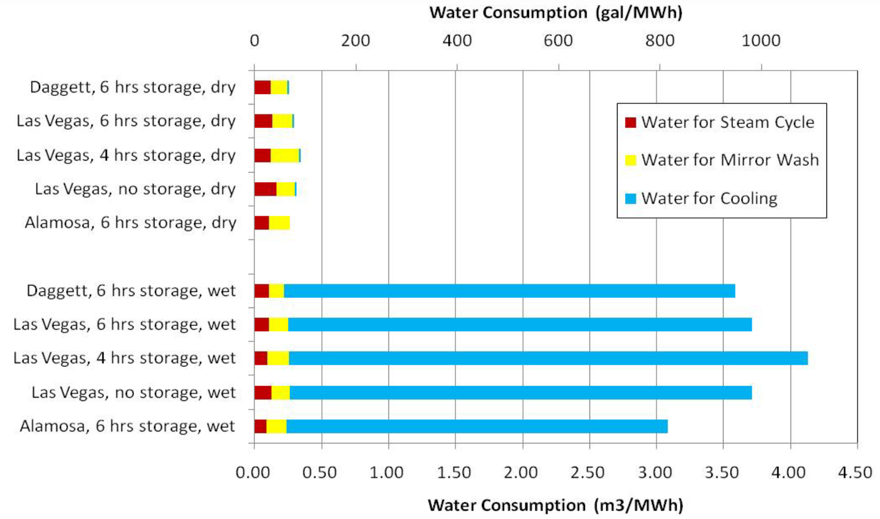

Figure 2.2. Dry cooling reduces CSP water consumption by over 90%.

Water Consumption: Figure 2.2 highlights a comparison of water consumption by the different plant designs considered by WorleyParsons. Switching to dry cooling reduces water consumption by more than 90%. In very hot climates, dry-cooled systems may require a small amount of cooling water to supply low-temperature cooling for turbine components, but this represents less than 0.3% of the original cooling water consumption. The remaining water consumption is split between steam-cycle maintenance and mirror washing. Steam-cycle water consumption increases slightly in dry-cooled plants due to the lower plant efficiency, but these effects are overwhelmed by eliminating the cooling tower.

The average water consumption per generation for the wet-cooled plants is 3.5 m^3/MWh; for the dry-cooled plants, it is 0.3 m^3/MWh. These values can be compared to water consumption at other wet-cooled Rankine cycle plants: about 2.2 m^3/MWh for coal and 3.2 m^3/MWh for nuclear, assuming closed-loop cooling towers with on-site evaporation ponds [Klara 2007, 2009]. Compared to these plants, water consumption for the trough plants is higher due to lower cycle efficiency and more frequent startup and off-design operation. Lacking any specific site data, WorleyParsons' assumed fixed cooling tower cycles of concentration (COC) and water cost for all locations. COC depends on water quality and variations in COC will affect overall water consumption.

Dry Cooling Impact on LCOE: Results of the WorleyParsons analysis reported in Turchi et al. indicate that switching from 100% wet to 100% dry cooling will result in LCOE increases of approximately 3% to 8% for parabolic trough plants throughout most of the southwestern United States. The least impact occurs in cooler, high-altitude areas like Alamosa, Colorado. The greatest impact is on plants without thermal energy storage in hot, desert regions. Thermal energy storage helps to mitigate the cost impact of dry cooling because some operating hours are shifted to cooler time periods. The cost impact on power tower systems will be less, because the higher operating temperatures of power towers reduces the performance impact caused by the heat rejection temperature.

Effect of TOD Rates: Many utilities offer time-of-delivery rates for power based on when the power is produced. Because several California utilities offer favorable TOD allocation factors for summer afternoons, solar plants in those locations receive a disproportionate amount of their revenue during the summer.

While summer-weighted TOD rates are generally favorable for solar plants, the relative penalty for dry cooling may be exacerbated by heavily weighted peak generation rates. To examine this possibility, the 2009 TOD rate schedules for Southern Cal Edison (SCE) and Pacific Gas & Electric (PG&E) were applied. The annual revenue was calculated for wet- and dry-cooled plants for an SCE schedule, which represents the most extreme TOD rates. For Alamosa weather, annual revenue falls 0.15% more than annual generation, while for the more challenging climate of Daggett, annual revenue lags annual generation by 0.43%. In these simulations, the steam turbine is allowed to run at up to 105% of its design rating during TOD period 1 (summer weekday afternoons). Overdesign operation during this period allows the plant to maximize production—and revenue—during periods of highest demand. When overdesign operation was not allowed, the TOD schedules had a greater impact on relative revenue, but the difference was still less than 0.5%.

Hybrid cooling, where an air-cooled condenser and wet-cooling tower are arranged in parallel, can minimize the LCOE increase due to 100% dry cooling, especially for cases where TOD rates favor power generation during hot afternoons. However, the parallel cooling system comes with a higher capital cost and operational complexity (see Figure 3). The economics of hybrid cooling depend on water cost, climate, and TOD rates.

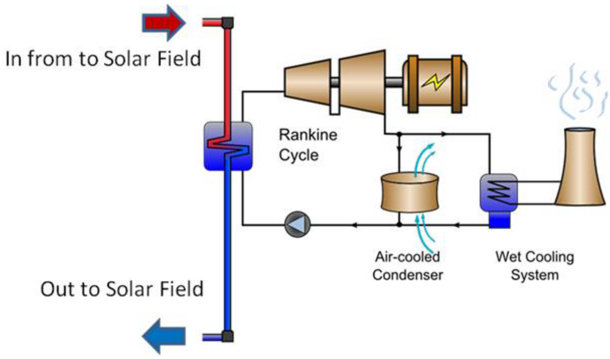

Figure 2.3. Parallel hybrid cooling systems use both wet and dry condensers to balance wet consumption and plant efficiency.

A study of hybrid cooling economics was reported by Wagner and Kutscher at SolarPACES 2010. Their results show that hybrid cooling offers an opportunity for significant reduction in water use compared to wet cooling while providing a noticeable improvement in a project's "bid price." The bid price is defined as the annual average cost of electricity that returns the desired return on investment based on the estimated revenue, plant cost, and operating expenses for the project. Bid price differs from LCOE for projects where revenue is a strong function of TOD market prices. Several trends in the results have application in the design of cooling systems:

- Bid price minimization (rather than straight LCOE minimization) better captures the potential advantages of hybrid cooling for markets with TOD pricing.
- The bid-price-optimized ACC for a hybrid plant is generally smaller than for a dry-cooled plant. While this results in reduced annual output, this loss is offset by reduced capital cost. The ACC can be smaller because the wet-cooling system can share the heat rejection load during periods of high ambient temperature. Therefore, the ACC design point temperature for hybrid cooling should represent average ambient conditions rather than the maximum operating temperature.
- Hybrid cooling during peak TOD periods can reduce the dry cooling bid price penalty by nearly two percentage points in hot climates, somewhat less in a cooler climate.

Hybrid cooling mitigates water use relative to traditional wet cooling, but the magnitude of the bid price reduction for hybrid cooling is inversely proportional to the amount of water used on an annual basis (Figure 4). Consequently, plants designed for heavily weighted TOD markets will benefit from maximizing water use during the hottest and most heavily weighted TOD periods. CSP plant design should account for the local water rights restrictions, but this analysis shows that strategic water use coupled with a bid-price-optimized design can provide an improvement in project rate of return.

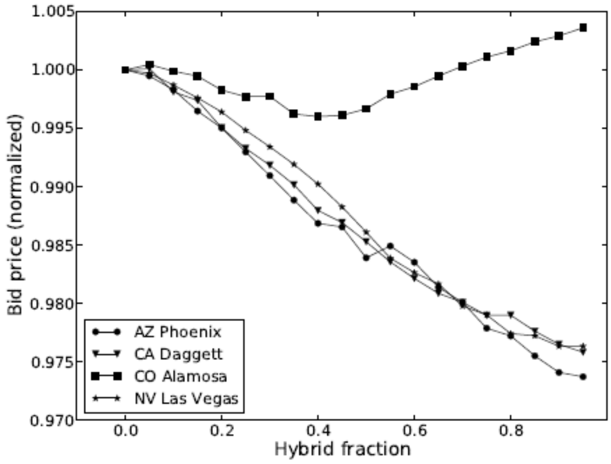

Figure 2.4. Bid price generally falls as a function of hybrid cooling fraction. Dry-cooled plant has hybrid fraction = 0; wet-cooled = 1.

<u>Conclusions & Future Work</u>: Switching from wet cooling to 100% air cooling will reduce CSP water consumption by over 90%. Such a change results in an increase in LCOE due to lower system efficiency during hot weather and higher equipment costs. The LCOE increase ranges from 3% to 8% for parabolic troughs, depending on weather conditions. The impact to power towers will be less.

These analyses showed hybrid cooling can provide revenue benefits in hot locations with TOD rate structures; however, full parallel hybrid systems significantly increase the capital cost of the heat rejection system. If the wet cooling component is used for relatively few hours per year, for example, due to limited water availability, such a capital expense may not be justified. Alternative hybrid cooling options, such as humidification of the ACC air intake or occasional water deluge of ACC coils may provide performance benefits at lower capital cost. Analysis of these designs is the subject of future work.

2.2 Dry cooling with Heller systems including cold water storage

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J. Dersch

Funding: German Ministry of Environment (Project Efcool, 130 k€ Funding, 2006 - 2008)

Several cooling configurations were modeled and compared for use at different sites. The solar field size was varied at constant capacity for a given configuration to find the lowest LCOE. A Heller System (Figure 2.5), which recovers waste heat and transfers it to a dry cooling tower through a water circuit that directly cools the steam turbine outlet, was also modeled. This minimizes the temperature difference necessary, but requires demineralized water, and includes water tanks for its operation. It was chosen here as an example showing the possibility of shifting cooling loads through intermediate storage of waste heat in large water tanks cooled at night at considerably ambient lower temperatures. The part load characteristic assumed for the Heller System is shown in Figure 2.6. The results of the analyses are summarized in Table 2.1. It may be observed that although storage improves the LCOE over the simple Heller System by about 2%, it is still less economical than conventional dry cooling (ACC).

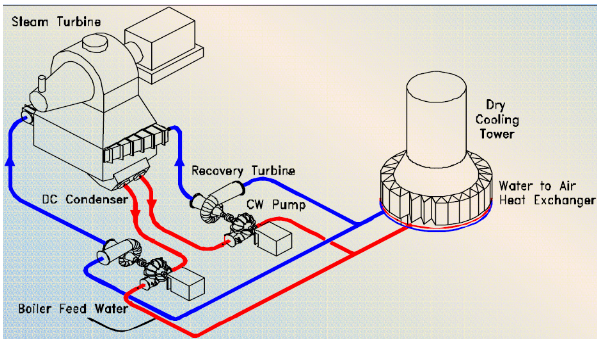


Figure 2.5. Layout of a Heller System (Source: EGI)

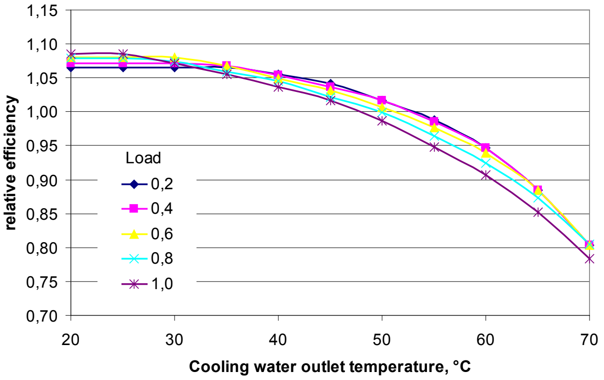


Figure 2.6. Heller System part load characteristic.

However, the technical performance (net output) resulting from simulation of the option with the lowest LCOE for the Heller System with storage yields an improvement compared to dry cooling, especially for the Barstow site. Therefore, depending on the revenues from time-dependent sales (TOD) and prices of the electricity generated, the overall economics of a cooling system with storage might be better than conventional dry cooling.

Summary**:** This analysis coincided with the general lines of the more recent one above, indicating that the use of direct or indirect dry cooling can eliminate about 90% of the water consumed in a water-cooled CSP plant. The drawback is an estimated annual increase of 2-10% in LCOE, due to reduction in power output, and higher investment and cost of operation for dry cooling equipment. The use of hybrid parallel wet/dry cooling is estimated to reduce the energy cost penalty to below that of air cooling alone while still saving about 80% of the

Table 2.1. Absolute values (first column, bold numbers, for the reference case of wet cooling) and relative changes in the different cooling options compared to sites in Barstow, CA, and southern Spain, for a Parabolic Trough Plant with 50 MW design capacity. Heller is Heller Cooling System, Stor is night-cooled water tanks (fan cooling) used to maintain the Heller System cooling water at the desired temperature (when possible) during hotter daily operating hours. 50000 m^3 storage tank, estimated price 30€/m^3 (tank+water filling). Changes are given as percentages, reductions (shown as negative) for differences are in italics. Economic figures are based on indicative, not binding offers, and do not necessarily represent real project costs).

Results	**Barstow, California**				**Seville, Spain**			
	Wet	**Heller**	**Heller Stor**	**Dry**	**Wet**	**Heller**	**Heller Stor**	**Dry**
Solar field size [1000 m2]	**298,2**	6,3%	10,4%	2,1%	**320,0**	5,8%	6,8%	2,9%
Net efficiency [%]	**13,6**	*-7,0%*	*-5,5%*	*-2,7%*	**13,7**	*-5,5%*	*-3,3%*	*-0,8%*
Net output [GWh]	**113,4**	*-1,2%*	4,3%	*-0,6%*	**88,1**	*0,0%*	3,3%	2,1%
LEC [€/kWh]	**0,137**	7,6%	5,4%	4,8%	**0,184**	6,3%	4,7%	2,7%
Specific Water consumption [m3/MWh]	**3,82**	*-84,4%*	*-84,5%*	*-91,6%*	**3,77**	*-83,5%*	*-83,6%*	*-90,9%*
Total investment [Million €]	**123,9**	8,4%	12,5%	6,2%	**130,3**	8,0%	10,1%	6,6%
O&M costs [€/kWh]	**0,029**	*-0,4%*	*-3,6%*	*-2,8%*	**0,038**	*-0,2%*	*-2,5%*	*-3,6%*

water compared to a water-cooled plant. Closed-loop water storage to shift cooling loads would avoid cooling water consumption and may improve performance compared to pure dry-cooling, but implies about a 3-5% increase in LCOE. Due to the complexity of the system and number of parameters to be adapted, detailed site specific analysis and further model refinement would be necessary to decide for the optimum cooling system configuration.

Some concepts for improving CSP cooling performance recently studied by other authors have considered the use of PCM storage materials to shift cooling loads (Pistoccini et. al.) and tall chimneys for natural draft (based on the updraft tower analysis) to avoid the high parasitic losses from fan operation in conventional dry cooling systems (Bonnelle et al.).

2.3 References:

[2.1] Klara, J., "*Cost and Performance Baseline for Fossil Energy Plants,*" DOE/NETL-2007/1281, Volume 1: Bituminous Coal and Natural Gas to Electricity, Revision 1, August 2007.; Water Requirements for Existing and Emerging Thermoelectric Plant Technologies, DOE/NETL-402/080108, April 2009.

[2.2] Turchi, C.S., M.J. Wagner, and C.F. Kutscher, "*Water Use in Parabolic Trough Power Plants: Summary Results from WorleyParsons' Analyses,*" NREL/TP-5500-49468, National Renewable Energy Laboratory, Golden, Colorado, USA, December 2010.

[2.3] Wagner, M.J., and C.F. Kutscher, "*Assessing the Impact of Heat Rejection Technology on CSP Plant Revenue*, SolarPACES 2010, Perpignan, France, September 21-24, 2010.

[2.4] C. Richter, J. Dersch, "METHODS FOR REDUCING COOLING WATER CONSUMPTION IN SOLAR THERMAL POWER PLANTS " presented at SolarPACES 2009 Conference, 15th September 2009, Berlin, Germany.

[2.5] L. Pistocchini, M. Motta. Feasibility Study of an Innovative Dry-Cooling System With PCM Storage for CSP Multi-MW Sized Power Plant. Proceedings of the Solarpaces Conference, 2010, Perpignan (Fr)

[2.6] D. Bonnelle, F. Siros and C. Philibert CONCENTRATING SOLAR PARKS WITH TALL CHIMNEYS DRY COOLING, Proceedings of the Solarpaces Conference, 2010, Perpignan (Fr)

3 Task I:
Solar Thermal Electric Systems

Operating Agent:
Mark S. Mehos
National Renewable Energy Laboratory

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, has been proposed and will likely be developed further in 2010. Each of these three subtasks will be described more fully later in this chapter.

3.3 Status of the Technology

Concentrating solar power offers the lowest cost option for large, utility-scale solar energy today, with expected un-incentivized production costs of less than 20¢/kWh for early commercial plants sited in locations with premium solar resources. Lower costs are expected where additional incentives for CSP systems are available (e.g. the existing U.S. Federal 30% Investment Tax Credit). As the cost of electricity from conventional generation technologies continues to rise, off-takers are becoming increasingly interested in CSP as a viable alternative to other renewable technology options. Concerns over global warming and the increasing likelihood of a global carbon constrained energy market, has further increased this interest.

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. As CSP and PV systems approach cost parity the ability of CSP plants to provide high value firm, dispatchable power through the use of thermal storage or hybridization with fossil fuels will become increasingly important.

Concentrating solar power today is represented by four technologies: parabolic troughs, linear Fresnel reflectors, power towers and dish/engine systems. Of these technologies, parabolic troughs, and more recently towers, have been deployed in commercial plants. Nine SEGS plants totaling 354 MW, originally built and operated by LUZ in California in the 1980s and 1990s, are continuing to operate today with performance of most of the plants improving over time. In 2006, two commercial CSP began full-scale operation. Acciona, formerly SolarGenix, completed construction of a 64-MW parabolic trough plant near Las Vegas, Nevada. The 64-MW plant was the first new commercial large-scale parabolic trough plant to begin operation in more than 15 years Abengoa inaugurated the first commercial central receiver plant, PS10, an 11 MW saturated steam central receiver plant located near Seville, Spain. Since these first plants, considerable progress has been made in the construction and development of plants throughout the world, demonstrating an increasingly optimistic outlook for CSP technologies of all configurations (see below for list of plants in operation or under construction). Over 380 MW of CSP systems are now operational in Spain and over 700 MW are currently under construction at the time of this report. Project totaling greater than 10 GW of capacity are under various stages of development, primarily in Spain, northern Africa, and the southwest U.S. (see project database task for more information on CSP projects in operation, under construction, or under development).

Parabolic troughs are today considered to be fully mature technology, ready for deployment. Early costs for solar-only plants are expected to be in the range of 0.17-0.20 $/kWh in sunny locations where no incentives are offered to reduce costs. In recent years, the five plants at the Kramer Junction site (SEGS III to VII) achieved a 30% reduction in operation and maintenance costs, record annual plant efficiency of 14%, and a daily solar-to-electric efficiency near 20%, as well as peak efficiencies up to 21.5%. Annual and design point efficiencies for the current generation of parabolic trough plants under construction in the U.S. and Spain are expected to be even higher, greater than 15%

and 23% respectively, based on higher performance mirrors and heat collection elements.

Hybrid solar/fossil plants have received much greater attention in recent years, and several Integrated Solar Combined Cycle (ISCC) projects are now under construction in the Mediterranean region and the U.S. New Energy Algeria (NEAL) selected Abengoa to build the first such project at Hassi-R'mel. The project will consist of a 150 MW ISCCS with 30 MW solar capacity. Similar projects are under construction in Morocco and Egypt. Archimede is another example of an ISCCS project, however the plant's 31,000 m^2 parabolic trough solar field will be the first to use a molten salt as a heat transfer fluid.

Advanced technologies like Direct Steam Generation (DISS) are under development at the Plataforma Solar de Almeria where researchers continue to compare direct steam, using a combination of sensible heat storage and latent heat storage, with oil heat transfer fluids. Abengoa has constructed several direct steam test loops at their test facility. Depending on results of these tests, Abengoa intends to implement commercial-scale direct steam. Research on higher temperature heat transfer fluids and lower-cost storage systems are also being pursued. Both Abengoa and Solar Millennium are developing systems that use molten salt in the field, increasing plant efficiency and reducing storage costs.

Linear Fresnel systems are conceptually simple, using inexpensive, compact optics, and are being designed to produce saturated or superheated steam. This technology may be suited for integration into combined cycle recovery boilers, i.e., to replace the bled steam in regenerative Rankine power cycles or for saturated steam turbines. Extensive testing experience at a prototype-scale has been underway for several years at the Liddell power station in Australia and the first commercial system linear Fresnel system, Puerto Errado I by Novetec, is now operational in Spain. Systems are also under development by (MAN/SPG (Germany), Ausra/Areva (U.S/France), and SkyFuel (U.S.).

Power tower technology, a.k.a. central receiver technology, have completed the proof-of-concept stage of development and, although less mature than parabolic trough technology, are on the verge of commercialization.

Construction of PS10, the first commercial power tower, was completed by Abengoa at its project site outside of Seville, Spain and has been operating successfully since 2007. The tower system uses a saturated steam receiver to deliver steam to an 11-MW saturated steam turbine. PS20, roughly double the size of PS10, started operation in 2009. Brightsource and eSolar are also developing steam-based receiver designs with the intent of delivering superheated steam at higher temperatures and pressures. eSolar's Sierra SunTower project, a 5-MW plant located at their test facility in Lancaster, California, began operation in 2009.

An alternative to steam receiver systems under development by Abengoa, Brightsource, and eSolar is the molten salt tower. This approach offers the potential for very low-cost storage that permits dispatch of solar electricity to meet peak demand periods and a high capacity factor (~70%). A molten-salt power tower three times larger than Solar Two is being designed by Sener for southern Spain. This plant, named Gemasolar, is a 17-MW molten-salt tower and is projected to start construction in 2010. U.S.-based Solar Reserve has signed agreements for 250 MW of tower projects with molten salt storage in Nevada and California.

Dish/engine systems are modular units typically between 5 and 25 kW in size. Stirling engines have been pursued most frequently, although other power converters like Brayton turbines and concentrated PV arrays have been considered for integration with dish concentrators. The high solar concentration and operating temperatures of dish/Stirling systems has enabled them to achieve world-record solar-to-electric conversion efficiencies of 30%. However, due to the level of development of these technologies, energy costs are about two times higher than those of parabolic troughs. Dish/engine system development is ongoing in Europe and the USA. Reliability improvement is a main thrust of ongoing work, where the deployment and testing of multiple systems enables more rapid progress. Dish/Stirling systems have traditionally targeted high-value remote power markets, but industry is increasingly interested in pursuing the larger, grid-connected markets.

In Europe, Schlaich Bergermann und Partner have extensively tested several 10-kW systems, based on a structural dish and the Solo 161 kinematic Stirling engine at the Plataforma Solar de Almería. Follow-up activities based on the EuroDish design are being pursued by a European Consortium of SBP, Inabensa, CIEMAT, DLR and others. EuroDish prototype demonstration units are currently being operated in Spain, France, Germany, Italy and India.

In the USA, Stirling Energy Systems (SES) is developing a 25-kW dish/Stirling system for utility-scale markets. Six SES dish/Stirling systems are currently being operated as a mini power plant at Sandia National Laboratories' National Solar Thermal Test Facility in Albuquerque, NM, USA. SES has two power purchase agreements to install 800 MW of these 25-kW systems in California, USA. Construction of a 1.5-MW facility is underway in Arizona.

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 proposed and will likely be developed further in 2010. Each of these efforts is described briefly below.

Table 3.1 CSP Systems in Operation

COMMERCIAL CSP SYSTEMS	Contact	*Sharing*			
		I	M	T	C
Operational Systems					
Alvarado I	Asun Padros - Acciona	x			
Andasol 1-2	Manuel Cortés - ACS Cobra	x			
Archimede	Massimo Falchetta - ENEA	x			
Central Solar Termoelectrica La Florida	Javier del Pico - Renovables SAMCA	x			
Colorado Integrated Solar Project	Marty Smith – Xcel	x			
Extresol 1-2	Manuel Cortes – ACS/Cobra	x			
Holaniku at Keahole Point	Darren Kimura	x			
Ibersol Ciudad Real	Iberdrola	x			
Kimberlina Power Station	David Mills - Ausra	x			
La Dehesa	Javier del Pico - Renovables SAMCA				
Liddell Power Station	David Mills - Ausra	x			
Majadas I	Asun Padrós - Acciona Energia	x			
Manchasol 1	Manuel Cortes – ACS/Cobra	x			
Maricopa Solar Project	Peter Becker – Stirling Energy Systems	x			
Nevada Solar One	Asun Padrós – Acciona Solar Power	x			
Palma del Rio 2	Asun Padrós - Acciona Energia	x			
Ps10/Ps20	Ana Cabañas – Abengoa Solar	x			
Puerto Errado 1	Wolfgang Gödde - Novatec Biosol	x			
Saguaro	Phil Smithers – Arizona Public Service	x			
Sierra SunTower	Jim Shandalov - eSolar	x			
SEGS I-II	Philip Jones - Cogentrix	x			
SEGS III-IX	Jennifer Swift – NextEra Energy Resources	x			
Solnova 1,3,4	Ana Cabañas – Abengoa Solar	x			

3.4.1 SolarPACES International Project Database

Contact: Mark Mehos, mark.mehos@nrel.gov
Funding: SolarPACES funded project, cost shared: € 25,000
Duration: January 1, 2008 - March 31, 2011

Background: SolarPACES has historically tracked and reported on the development, construction, and operation of commercial CSP projects throughout the world. Given the explosion of growth in CSP in Spain beginning in 2009, and subsequent interest in the development of CSP projects primarily in the U.S. and MENA region, it was proposed that Task I should create a more dynamic project database. The database was brought online in 2009 and currently includes voluntary contributions from SolarPACES member countries including Algeria, Germany, Italy, Spain, Algeria, Egypt, Germany, Italy, Morocco, and the U.S. The database currently provides information on xx plants in operation, yy plants under construction, and zz plants under development.

Achievements in 2010: The database currently provides detailed information on 35 plants in operation. Table 1 provides a current listing of the operational CSP systems worldwide at the end of 2010. Details for these projects and well as projects under construction or operation can be viewed at the SolarPACES project site located at http://www.solarpaces.org/News/Projects/projects.htm.

The database provides a listing of solar projects by country, project name, technology, or status as shown in Figure 3.1 on the following page. Figure 3.2 provides a listing of all of the projects currently listed in the database, including those systems in operation, under construction, or under development.

In order to accommodate the rapidly expanding listing of projects under construction and development, a means for web-based entry of data has been developed (see Figure 3). Points of contact will be identified for each SolarPACES member country. Each contact will be responsible for gathering and inputting information for each project within their country and/or region.

Future Work: There have been numerous requests for additional information to be displayed within the SolarPACES project database. For example, graphical representations of plant installation by technology and by year would be useful for displaying technology trends. Updates to the database will be made based on feedback received from the SolarPACES community.

Working with member countries, SolarPACES—Solar Power and Chemical Energy Systems—has compiled data on concentrating solar power (CSP) projects around the world that have plants that are either operational, under construction, or under development. CSP technologies include parabolic trough, linear Fresnel reflector, power tower, and dish/engine systems.

For individual concentrating solar power projects, you will find profiles that include background information, a listing of participants in the project, and data on the power plant configuration.

These pages should help utilities, financiers, manufacturers, and anyone interested in renewable-energy options to find information on the growing number of concentrating solar power projects around the world.

Browse the Project Profiles

You can browse project profiles under the following categories:

- Country—listing by one of 9 countries
- Project name—alphabetical listing by full project name
- Technology—listing by parabolic trough, linear Fresnel reflector, power tower, or dish/engine systems
- Status—listing by whether projects have plants that are operational, under construction, or under development.

About the Project Profiles

The National Renewable Energy Laboratory's CSP Program assists SolarPACES in maintaining the projects database behind this Web site. Project operators or developers supply information for the key data fields for their projects. SolarPACES experts then review the information to ensure accuracy and completeness. The material is updated regularly, and because this site is new, we are still expanding the number of projects, especially those that are under development.

SolarPACES Snapshot

SolarPACES, an international program of the International Energy Agency, furthers collaborative development, testing, and marketing of concentrating solar power plants. Activities include testing large-scale systems and developing advanced technologies, components, instrumentation, and analysis techniques. Three ongoing Tasks are Concentrating Solar Electric Power Systems, Solar Chemistry Research, and Solar Technology and Applications.

Founded in 1977, SolarPACES now has 13 members: Algeria, Australia, Egypt, the European Commission, France, Germany, Israel, Mexico, South Africa, South Korea, Spain, Switzerland, and the United States.

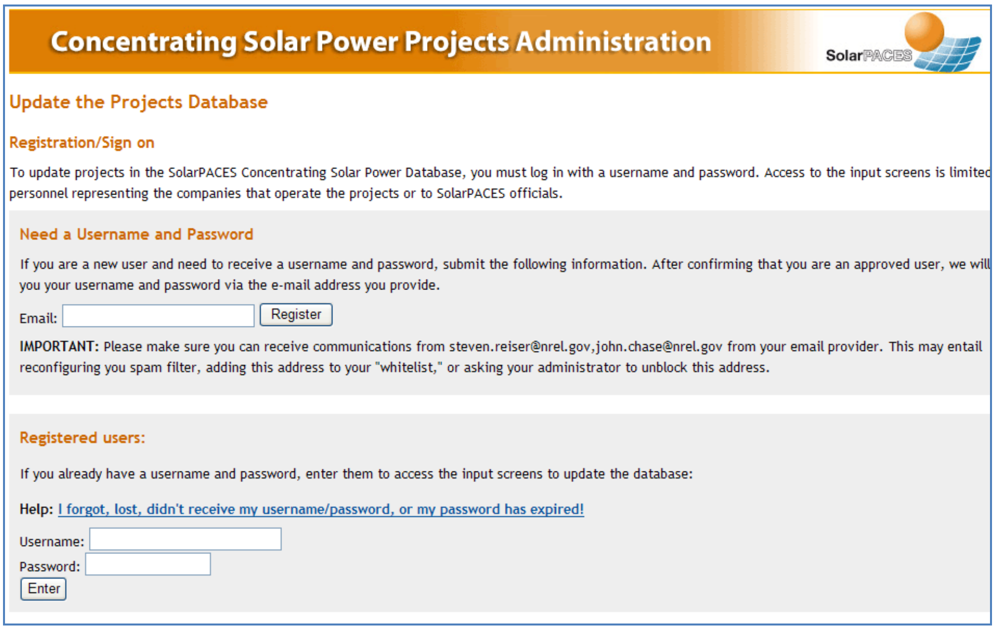
Figure 3.1. Start-up page for CSP project database.

Concentrating Solar Power Projects by Project Name

In this section, you can select a concentrating solar power (CSP) project from the alphabetical listing of project names below. You can then review a profile covering project basics, participating organizations, and power plant configuration data for the solar field, power block, and thermal energy storage.

- Abengoa Mojave Solar Project
- Alvarado I
- Andasol-1 (AS-1)
- Andasol-2 (AS-2)
- Andasol-3 (AS-3)
- Andasol-4 (AS-4)
- Archimede
- Arcosol 50 (Valle 1)
- Blythe Solar Power Project
- BrightSource Coyote Springs 1 (PG&E 3) (Coyote Springs 1)
- BrightSource Coyote Springs 2 (PG&E 4) (Coyote Springs 2)
- BrightSource PG&E 5
- BrightSource PG&E 6
- BrightSource PG&E 7
- Central Solar Termoelectrica La Florida (La Florida)
- Colorado Integrated Solar Project (Cameo)
- Crescent Dunes Solar Energy Project (Tonopah)
- EL REBOSO II 50-MW Solar Thermal Power Plant (El Reboso II)
- EL REBOSO III 50-MW Solar Thermal Power Plant (El Reboso III)
- Extresol-1 (EX-1)
- Extresol-2 (EX-2)
- Extresol-3 (EX-3)
- Gaskell Sun Tower (Gaskell)
- Gemasolar Thermosolar Plant (Gemasolar)
- Genesis Solar Energy Project
- Helios I (Helios I)
- Helios II (Helios II)
- Holaniku at Keahole Point
- Ibersol Ciudad Real (Puertollano)
- Imperial Valley-Solar Two
- ISCC Argelia (ISCC Argelia)
- ISCC Morocco (ISCC Morocco)
- ISCCS Al Kuraymat (ISCCS Al Kuraymat)
- Ivanpah Solar Electric Generating Station (ISEGS)
- Kimberlina Solar Thermal Power Plant (Kimberlina)
- La Dehesa
- Lebrija 1 (LE-1)
- Majadas I
- Manchasol-1 (MS-1)
- Manchasol-2 (MS-2)
- Maricopa Solar Project (Maricopa)
- Martin Next Generation Solar Energy Center (MNGSEC)
- Nevada Solar One (NSO)
- NextEra Beacon Solar Energy Project (Beacon)
- Palen Solar Power Project
- Palma del Río I
- Palma del Río II
- Planta Solar 10 (PS10)
- Planta Solar 20 (PS20)
- Puerto Errado 1 Thermosolar Power Plant (PE1)
- Puerto Errado 2 Thermosolar Power Plant (PE2)
- Rice Solar Energy Project (RSEP)
- Saguaro Power Plant
- Shams 1 (Shams 1)
- Sierra SunTower (Sierra)
- Solana Generating Station (Solana)
- Solar Electric Generating Station I (SEGS I)
- Solar Electric Generating Station II (SEGS II)
- Solar Electric Generating Station III (SEGS III)
- Solar Electric Generating Station IV (SEGS IV)
- Solar Electric Generating Station V (SEGS V)
- Solar Electric Generating Station VI (SEGS VI)
- Solar Electric Generating Station VII (SEGS VII)
- Solar Electric Generating Station VIII (SEGS VIII)
- Solar Electric Generating Station IX (SEGS IX)
- Solnova 1
- Solnova 3
- Solnova 4
- Vallesol 50 (Valle 2)

Figure 3.2. Database listing of CSP projects by project name



Concentrating Solar Power Projects Administration

Update the Projects Database

Registration/Sign on

To update projects in the SolarPACES Concentrating Solar Power Database, you must log in with a username and password. Access to the input screens is limitec personnel representing the companies that operate the projects or to SolarPACES officials.

Need a Username and Password

If you are a new user and need to receive a username and password, submit the following information. After confirming that you are an approved user, we will you your username and password via the e-mail address you provide.

Email:

IMPORTANT: Please make sure you can receive communications from steven.reiser@nrel.gov,john.chase@nrel.gov from your email provider. This may entail reconfiguring you spam filter, adding this address to your "whitelist," or asking your administrator to unblock this address.

Registered users:

If you already have a username and password, enter them to access the input screens to update the database:

Help: I forgot, lost, didn't receive my username/password, or my password has expired!

Username:

Password:

Figure 3.3. Web-based data entry screen

3.4.2 Development of Guidelines for CSP Performance Models

Participants: Abengoa (E), ANU (AUS), CENER (E), Ciemat (E), CSP Services (D), CSIRO (AUS), DLR (D), FhG-ISE (D), Flabeg (D), Flagsol (D), IMDEA (E), Novatec-Biosol (D), NREL, (USA), Politecnico Milano (I), Purdue University (USA), Sandia (USA), Skyfuel (USA), Solar Millennium (D), Suntrace (D), Torresol (E), Uni. Arizona (USA), Uni. Seville (E)
Contact: Markus Eck, markus.eck@dlr.de
Funding: SolarPACES funded project, cost shared: € 25,000
Duration: April 1, 2010 - March 31, 2011

Background: Electricity yield prediction for CSP plants is required during the whole process of project development, such as feasibility studies, project development or due-diligence studies. So far, no common standard methodology exists for this task. Accordingly, every stakeholder uses his own proprietary methodology and tool for yield prediction. This situation leads to a huge effort for tool development for every stakeholder and an unacceptable deviation of the model results resulting in increased project costs.

Objectives: The aim of this project is to develop a standard methodology (not a tool) for electricity yield prediction. The methodology will define a common frame work applicable to all CSP technologies and cover all relevant aspects such as appropriate system modeling, requirements of input data, consideration of transients, operation strategies and uncertainties in input and model parameters. Furthermore, appropriate economic figures of merit and validation procedures will be defined. Finally, a hand book will be published, presenting among others appropriate modeling approaches, default values for model parameters and uncertainties, guidelines for handling uncertainties, transients and operation strategies and data sets for model benchmarking.

Achievements in 2010: A coordination team was founded and a project structure was set-up, subdividing the project in ten work-packages. A first project meeting took place in parallel to the last SolarPACES conference in Perpignan to gather collaborators for the different work-packages and kick-start the activities. Meanwhile more than 80 international experts have agreed to support the project. As first steps, a first draft for the structural framework was prepared, a WiKi system was purchased to support the day-to-day work of the different work-packages and a model benchmarking for interested participants has started.

Publications:

[3.1] Eck M., Benitez D., Hirsch T., Ho C., Wagner M.: The First Steps Towards a Standardized Methodology for CSP Electricity Yield Analysis, In: Proceedings of the SolarPACES 2010 conference. 2010, 21-24 Sep 2010, Perpignan, France

[3.2] Eck M., Buck R., Dersch J., Feldhoff F., Giuliano S., Hennecke K., Hirsch T., Lüpfert E., Schwarzbözl P.,: Modelling, Simulation and Assessment of Solar Thermal Power Plants – A First Step Towards Definition of Best Practice Approaches, Proceedings of ES2010 Energy Sustainability, May 17-22 (2010) Phoenix, USA

3.4.3 Performance Acceptance Test Guidelines for Parabolic Trough Solar Fields

Participants: NREL (USA)
Contact: Mark Mehos, mark.mehos@nrel.gov
Funding: US DOE ($xx), cost share
Duration: April, 2008 – March, 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, has 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

Objectives: The objective of this activity is to develop interim guidelines for test procedures that can yield results of a high level of accuracy consistent with good engineering knowledge and practice. While the current guidelines are being 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.

Achievements in 2010: 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. x.1]. Based on the reviews from these two events, the draft was revised and expanded, with an expected completion and distribution of the final Guidelines report in early 2011 and publication as a SolarPACES report upon subsequent approval by the ExCo committee.

Summary of Guidelines content: 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. 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 an analytical performance 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. As shown in Figure 3.4, the power block and balance-of-plant are not within the boundaries of the guideline, nor does the scope of the guideline include a thermal storage system.

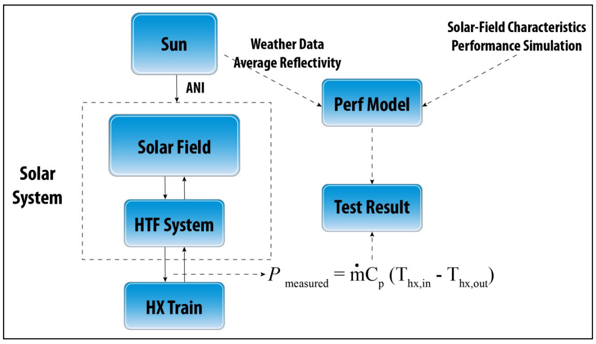


Figure 3.4. Scope of Performance Accetance Test Guidelines

The guideline describes two primary acceptance tests. The first – the *Short-duration Steady-State Thermal Power Test* – provides guidelines for measuring 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. Important issues related to both thermal equilibrium and stabilized test conditions are dealt with in considerable detail in this section. The second – *the Multi-Day Continuous Energy Test* – provides guidelines for collecting continuous daily thermal energy output (integrated power output) and efficiency data.

Test methods are recommended for both the short-term thermal power test and multi-day continuous energy test. Of special importance are the criteria that must be satisfied by the short-term power test in which the test 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.

Publications:

[3.3] Kearney, D., Mehos, M., (2010), Development of Performance Acceptance Test Guidelines for Large Commercial Scale Parabolic Trough Solar Fields, *SolarPACES 2010 Symposium,* Sep. 21–24, 2010, Perpignan, France.

4 Task II: Solar Chemistry Research

Operating Agent:
Anton Meier, PSI, Switzerland

National Coordinators:

- Keith Lovegrove, ANU, Australia
- Gilles Flamant, PROMES-CNRS, France
- Karl-Heinz Funken, DLR, Germany
- Michael Epstein, WIS, Israel
- Paolo Favuzza, ENEA, Italy
- Yong-Heack Kang, KIER, Korea
- Claudio Estrada, UNAM, Mexico
- Jan van Ravenswaay, NWU, South Africa
- Alfonso Vidal, CIEMAT, Spain
- Anton Meier, PSI, Switzerland
- Alan Weimer, UC, USA

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, 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 2010, we welcomed Jan van Ravenswaay from North-West University as the new NC for South Africa. The Task II Annual Meeting provides a forum for presenting and discussing major technological achievements.

The Task II Program of Work provides 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 2010, 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 2010, solar chemistry research was presented at three major international conferences:

- *16th SolarPACES Conference*, Perpignan, France, September 21-24, 2010: 20 papers were presented on solar fuels.
- *ASME 4th Int. Conf. on Energy Sustainability,* Phoenix, USA, May 17-22, 2010: 12 papers were presented on solar thermochemistry.
- *18th World Hydrogen Energy Conference*, Essen, Germany, May 17-20, 2010: 11 talks and 9 posters were presented on solar thermochemical production of hydrogen.

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. A progress review of this project has been published in 2010 [4.1]. Factsheets of various high-temperature thermochemical processes have been prepared.

In the following, the most important achievements in 2010 of Task II related projects are summarized with up-to-date information about project participation, objectives, status, and relevant publications.

4.2.1. Solar Production of Energy Carriers

SOLHYCARB – High Temperature Solar Chemical Reactors for Co-production of Hydrogen and Carbon Black from Natural Gas Cracking

Participants:	CNRS-PROMES (F), ETH (CH), PSI (CH), WIS (IL), CERTH/CPERI (GR), DLR (D), TIMCAL (B), SOLUCAR R&D (E), CREED (F), N-GHY (F)
Contacts:	Gilles Flamant, flamant@promes.cnrs.fr S. Abanades, abanades@promes.cnrs.fr
Funding:	EC funded project, cost shared: € 1,900,000
Duration:	March 1, 2006 – February 28, 2010

Background: The SOLHYCARB project addresses the solar thermal decomposition of natural gas (NG) or methane for the clean coproduction of hydrogen (H_2) and Carbon Black (CB). This process appears as an alternative to steam methane reforming and the furnace process for conventional production of H_2 and CB, respectively. The solar process avoids CO_2 emissions both from the fossil fuel combustion required for the endothermic reactions and from the steam reforming reaction, thus saving 13.9 kg-equivalent CO_2 per kg of H_2 produced compared to conventional processes [4.2]-[4.4].

Purpose: The research aims at designing, constructing, and testing innovative solar reactor prototypes at powers of 20 kW_{th} and 50 kW_{th} for performance evaluation between 1400°C and 1800°C. The targeted results are: (1) CH_4 conversion over 80%; (2) H_2 yield over 75%; and (3) CB properties equivalent to industrial products.

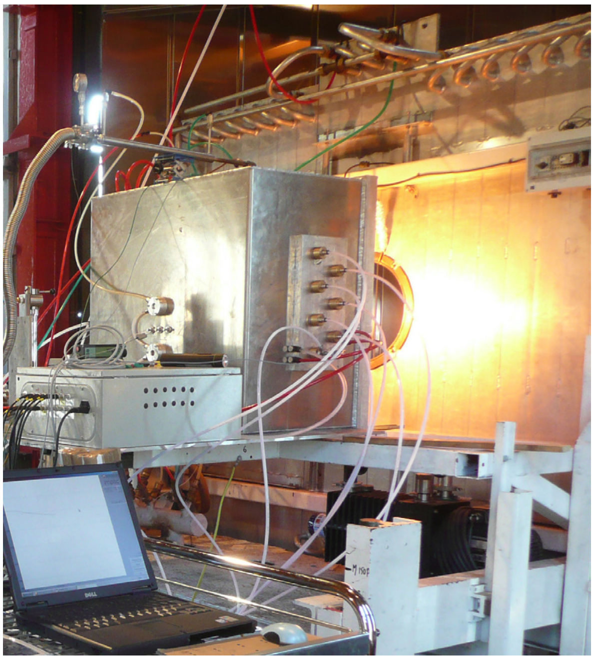


Figure 4 1. The 50-kW_{th} solar reactor in the focus of the CNRS 1-MW solar furnace during cooling.

Achievements in 2010: Figure 4 1 shows a 50-kW_{th} pilot-scale solar reactor that was designed and operated in the CNRS 1-MW solar furnace [4.4]. The solar reactor was a graphite cavity-type receiver containing seven tubular reaction zones. Temperature measurements around the cavity showed a homogeneous temperature distribution (Figure 4 2). The influence of temperature (1608-1928 K) and residence time (37-71 ms) on CH_4 conversion, H_2 yield, and C yield was investigated. CH_4 conversions were from 72% to 100% and H_2 yields from 57% to 88%. The carbon yield never exceeded 63%. For 900 g/h of CH_4 injected (50% molar, the rest argon) at 1800 K, this reactor produced 200 g/h H_2 (88% H_2 yield), 330 g/h CB (49% C yield) and 340 g/h C_2H_2. Thermochemical and thermal efficiencies up to 13.5% and 15.2% were achieved, respectively. C_2H_2 was the most important by-product, the amount of which was decreased by increasing the residence time.

In spite of a relatively low carbon yield due to the production of significant amounts of C_2H_2, representative quantities of CB were recovered for further characterization. The temperature of CH_4 dissociation is the main parameter that influences the specific surface area of carbon (in the 60-100 m²/g range). The structure and conductivity of a sample taken at the highest temperature (1928 K) approached the reference properties of commercial conductive CB. A 2D thermal model of the reactor revealed that the design of the reactor front face could be drastically improved to lower thermal losses. With the optimized design, efficiencies could reach 66%, i.e., 77% of the ideal blackbody absorption efficiency of 86% at 1800 K.

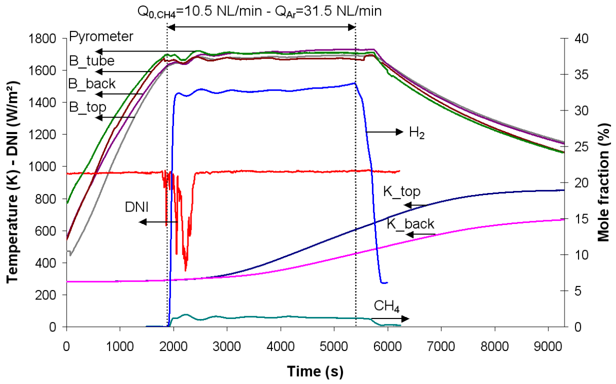


Figure 4 2. Online monitoring of temperatures, direct normal irradiance (DNI), H_2 and CH_4 off-gas mole fractions.

At ETH, a reactor model combining radiation/convection/conduction, heat transfer and chemical kinetics in a two-phase solid-gas reacting flow was designed [4.5]. The reactor was experimentally validated by comparing measured and simulated absorber temperatures and H_2 concentrations for a 10-kW_{th} prototype reactor tested in a solar furnace. The model was applied to optimize the design and simulate the performance of a 10-MW_{th} commercial-scale reactor mounted on a solar tower. Complete conversion is predicted for a maximum CH_4 mass flow rate of 0.70 kg s^{-1} and a desired outlet temperature of 1870 K, yielding a solar-to-chemical energy conversion efficiency of 42% and a solar-to-thermal energy conversion efficiency of 75%.

Publications: [4.2]-[4.5]

SYNPET – Hydrogen Production by Steam-Gasification of Petcoke

Participants: PDVSA (Venezuela), CIEMAT (E), ETH/PSI (CH)
Contact: Alfonso Vidal, alfonso.vidal@ciemat.es
Juan C. de Jesús, dejesusjc@pdvsa.com
Aldo Steinfeld, aldo.steinfeld@eth.ch
Funding: PDVSA-CIEMAT-ETH: $ 8,300,000
Duration: January 1, 2003 – February 28, 2011

Background: A joint PDVSA, CIEMAT and ETH project aims to develop and test a 500-kW$_{th}$ solar reactor for 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 SSPS/CRS tower 40-m platform 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 500-kW$_{th}$ pilot solar reactor.

Achievements in 2010: Following the test program, performance evaluation of the 500-kW$_{th}$ solar gasification plant on the SSPS/CRS tower progressed considerably in identifying and solving key technical problems. For a schematic layout of the system see [4.6].

Initial thermal tests aimed at checking an improved absorber configuration, which was manufactured by CIEMAT according to detailed information provided by ETH, based on their previous experience. The experimental results confirmed good performance both in stability and degradation. Further testing is in progress with a number of steady-state runs for evaluating the reactor performance under varying solar flux conditions, mass flow rates, and feed gas compositions (Figure 4 3).

The current test campaign also includes comprehensive evaluation to detect the operating limits of an innovative segmented quartz window with a 1.4-m diameter. Such a solar reactor window design, applicable for large focal spots, represents a technical challenge for the advancement of thermochemical applications in central receiver systems.

Final solar testing is scheduled for a period of six months in 2011. 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.

Publication: [4.6]

SOLSYN – Solar Process for High Quality Syngas from Carbonaceous Materials

Participants: PSI/ETH (CH), Holcim (CH)
Contact: Christian Wieckert, christian.wieckert@psi.ch
Funding: Swiss federal funding (CTI) + industry: € 1,300,000 (2nd phase)
Duration: Aug 1, 2009 – July 31, 2011 (2nd phase)

Background: In a first project phase in 2007-2009, laboratory tests with a two-cavity batch solar reactor (Figure 4 4) demonstrated the feasibility of solar steam gasification for a wide range of carbonaceous feedstock [4.7], [4.8].

Purpose: The main project goal is to develop and operate an innovative 250 kW$_{th}$ solar pilot reactor for steam

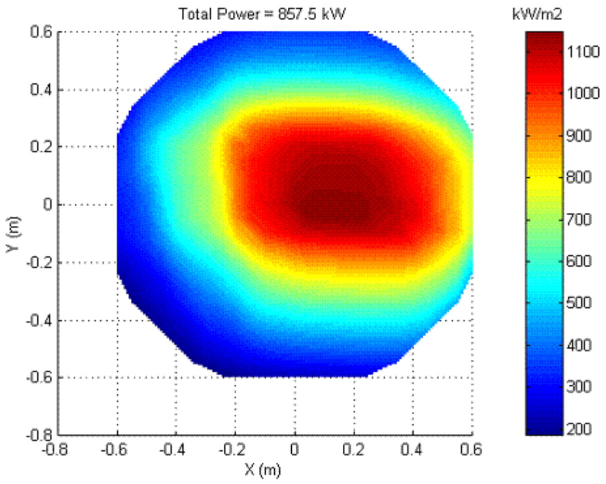


Figure 4 3. Flux distribution on the receiver aperture during the second test campaign for solar steam gasification of petcoke.

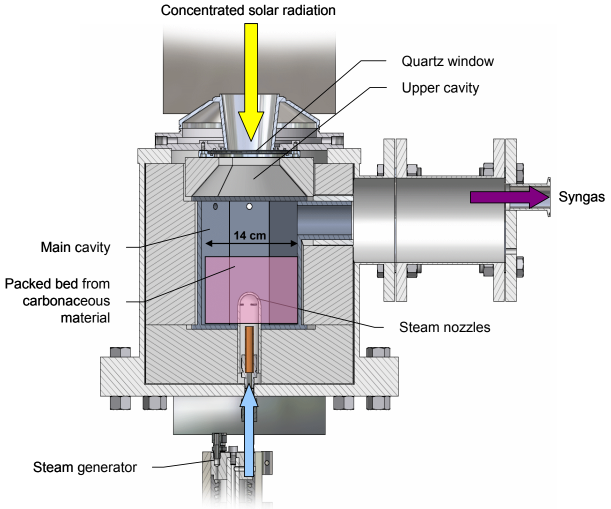


Figure 4 4. Schematic representation of a two-cavity batch reactor for solar steam gasification of carbonaceous materials to produce syngas.

gasification of coal, coke, and carbonaceous waste materials. Main process product is a synthesis gas (syngas, consisting mainly of H_2 and CO), which has a higher calorific value than the feedstock material ("solar upgrade"). The syngas is intended to be used directly as fuel for the main firing of cement kilns.

Achievements in 2010: In the second stage of the project, a 250-kW_{th} pilot plant was assembled. Further details and publishable results are expected to become available in 2011. A kinetic model has also been completed to support the numerical simulation of the complex processes taking place in the packed bed solar reactor [4.9].

Publications: [4.7]-[4.9]

Solar CO_2 Reforming of Methane for Synthesis Gas Production

Participants: Inha University (KOR)
Contact: Seo Taebeom, seotb@inha.ac.kr
Funding: National Research Foundation of Korea: € 103,423
Duration: May 1, 2009 – April 30, 2012

Background: Solar CO_2 reforming of methane to syngas is a topic of considerable interest for CO_2 utilization and natural gas conversion due to its important advantages over steam reforming of methane. This work proposed to the National Research Foundation is based on activities performed in a previous solar steam reforming project.

Purpose: The main purpose of this project is to develop and operate a 5-kW_{th} solar reformer for CO_2 reforming of methane.

Achievements in 2010: Solar CO_2 reforming of methane was successfully tested with a direct-irradiated absorber on a parabolic dish capable of providing 5-kW_{th} solar power (Figure 4 5). A new type of catalytically activated metal foam absorber was fabricated, and its activity was tested. Ni was applied as the active metal on the gamma-alumina coated Ni metal foam. Compared to the conventional catalytically activated ceramic foam absorber, direct irradiation of this new metallic foam absorber was found to exhibit superior reaction performance at relatively low insolation or at low temperatures. In addition, the metal foam absorber has better thermal resistance, which prevents cracking by mechanical stress or thermal shock. The total solar power absorbed was up to 2.1 kW_{th} and the maximum CH_4 conversion was almost 40% [4.10].

Figure 4 5. Solar Dish System (INHA-DISH1) with 5-kW_{th} absorber used for CO_2 reforming of methane.

Publication: [4.10]

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

Participants: CNRS-PROMES (F), CNRS-IEM (F)
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Gilles Flamant, flamant@promes.cnrs.fr
Funding: CNRS (F), ANR (F)

Background: Two-step thermochemical cycles based on metal oxide redox pairs (M_xO_y/M_xO_{y-1}) are promising routes to split H_2O and/or CO_2 and to produce clean H_2 and/or CO from high-temperature solar heat and abundant feedstock as only inputs. These cycles may entail either volatile oxides (e.g., ZnO/Zn or SnO_2/SnO) or non-volatile oxides such as ferrites. Besides the H_2O/CO_2-splitting and H_2/CO-generation step, all cycles involve a high-temperature step for the endothermic metal oxide reduction reaction, which takes place in a solar reactor.

Purpose: The goal of this study was to design and qualify novel efficient solar reactors operating at high temperatures over 1900 K suitable for the ZnO/Zn and SnO_2/SnO thermochemical water-splitting cycles [4.11]-[4.13]. The research also addresses investigation of reaction kinetics, performance evaluation and optimization of innovative solar reactor concepts.

Achievements in 2010: The high-temperature thermal dissociation reaction of ZnO and SnO_2 was investigated as part of a two-step thermochemical H_2O/CO_2-splitting cycle for H_2/CO production. A 1-kW_{th} lab-scale solar reactor was designed, built, and operated for continuous dissociation of volatile oxides in a controlled atmosphere under reduced pressure [4.13]. The reactor design allows the reaction front to be moved for continuous reactant feeding. ZnO and SnO_2 thermal dissociations were successfully performed at about 1900 K, with recovery up to 50% of products, such as high specific surface area nanopowders (in the 20-60 m^2/g range) and with mass fractions of reduced species up to 48 wt% for Zn and 72 wt% for SnO (Figure 4 6).

The reactor sustained repeated solar tests without noteworthy cavity material degradations. Each test produced about one gram of powder with significant fractions of reduced species in less than half an hour for a pressure of 20 kPa and a minimum inert gas dilution ratio of 36. Its typical average thermochemical efficiency (1-3% range) over the experiment duration was consistent with the one expected for small-scale reactors.

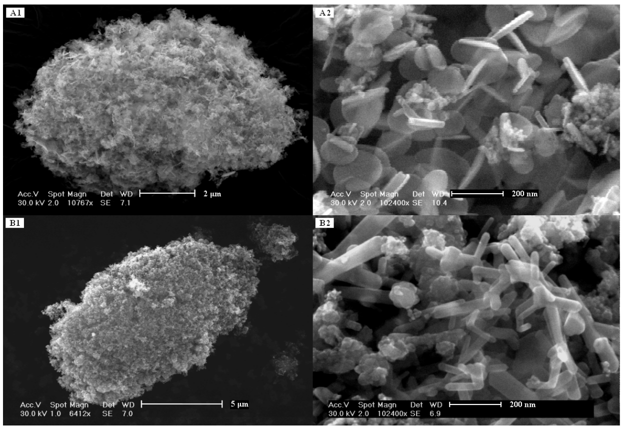

Figure 4 6. *Solar-produced nanopowders of SnO (top) and Zn (bottom) forming µm-scale agglomerates (left).*

The O_2 measurements performed (Figure 4 7) confirmed the kinetics of ZnO dissociation and resulted in activation energy of 380±16 kJ/mol, based on an ablation regime at the ZnO surface. The high specific surface area of the recovered powders provides favorable kinetics in the subsequent H_2O/CO_2-splitting step.

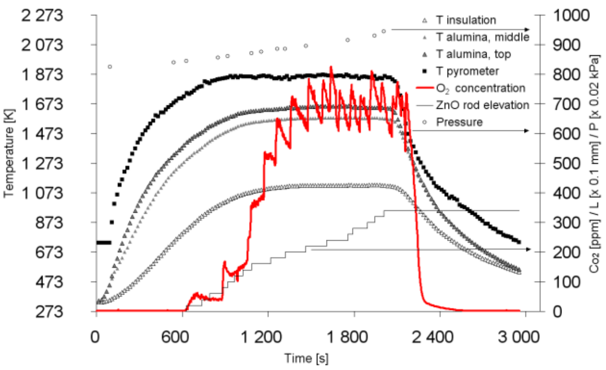

Figure 4 7. *Temperatures and O_2 concentration measured in the solar reactor for ZnO dissociation. The shutter was fully opened at time zero and closed at 2150 s.*

Publications: [4.11]-[4.13]

Zn-based Thermochemical Cycle for Splitting H_2O and CO_2

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Funding:	SFOE − Swiss Federal Office of Energy
Duration:	January 1, 2003 – June 30, 2012

Background: The production of H_2 and/or CO from H_2O and/or CO_2 in a two-step solar thermochemical cycle is being investigated. The first, endothermic step is the thermal dissociation of ZnO(s) into Zn(g) and O_2 at temperatures above 2000 K using concentrated solar energy as the source of process heat. The second, non-solar, exothermic step is the re-oxidation of Zn with H_2O and/or CO_2 to H_2 and/or CO, while the initial metal oxide, ZnO, is recycled to the first step [4.14].

Purpose: The main objective of 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}). Two experimental campaigns are scheduled for 2011 and 2012 at the PROMES-CNRS 1-MW Solar Furnace (MWSF) in Odeillo, France.

Achievements in 2010: The design and fabrication of a 100-kW_{th} pilot plant for the solar thermal dissociation of ZnO is in progress. The reactor features a rotating cavity receiver lined with ZnO particles distributed on the cylindrical walls. With this arrangement, ZnO is directly exposed to concentrated solar radiation entering

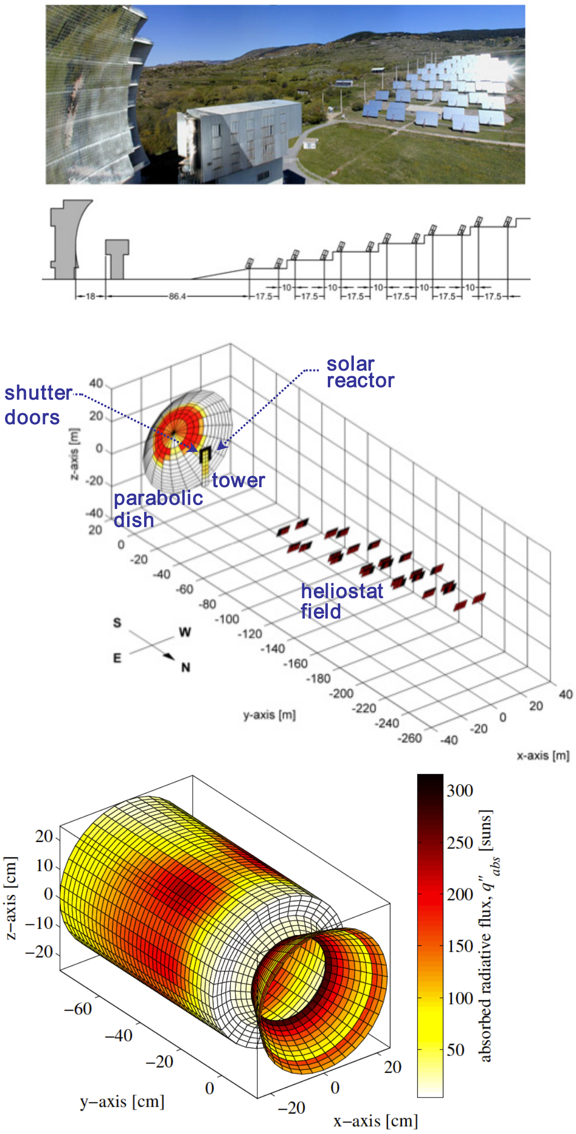

Figure 4 8. *Photograph and elevation of the MWSF in Odeillo, France (top). Setup of heliostat field, parabolic dish, and tower used for the ray-tracing model (middle) to compute the radiative flux distribution on the frustum-shaped front of the reactor and inside the rotary cavity (bottom). Experimental flux measurement data of the MWSF are provided by CNRS-PROMES.*

through a transparent quartz window and simultaneously serves the functions of radiant absorber and chemical reactant. A screw conveyor allows the batch addition of ZnO particles into the reactor cavity throughout the duration of the experiment. A major challenge is the design and fabrication of a Zn/O_2 separation device, which is based on the rapid quenching of the gaseous Zn/O_2 mixture with inert gas (argon) at the reactor cavity outlet. CFD simulations and flow visualization experiments have been performed to determine the optimal gas flow configuration to prevent the precipitation of condensing gas on the transparent quartz window.

An in-house Monte Carlo (MC) ray-tracing code was adapted to the geometry of the MWSF for computing the radiative flux distribution on the frustum-shaped front of the reactor and within the rotary cavity (Figure 4 8). According to MC ray-tracing and 3D heat transfer modeling, up to 40% of the total incoming radiation would be absorbed by the front (frustum) of the reactor and could lead to severe overheating of this component. Simulations indicate that the replacement of the Al_2O_3 frustum by a water-cooled metal equivalent would solve this problem with no significant detrimental effect to the energy conversion efficiency [4.15]. The model predictions for the 100-kW_{th} pilot reactor will be validated with experimental data obtained at the MWSF.

Publications: [4.14]-[4.15]

Solar Syngas Production from H_2O and CO_2 via two-Step Thermochemical Cycles

Participants:	ETH (CH)
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Funding:	Swiss National Science Foundation: CHF 159,414
Duration:	January 1, 2010 – December 31, 2012

Background: The object of this project is to examine the chemical thermodynamics, kinetics, and combined heat and mass transfer in gas-solid thermochemical reactions for chemically reducing CO_2 to CO or mixtures of CO_2/H_2O to synthesis gas (syngas) with metal oxide redox pairs in a two-step solar thermochemical cycle (Figure 4 9). The cycle encompasses 1) the thermolysis of a metal oxide to a lower valence metal oxide or metal and O_2 using concentrated solar radiation; and 2) the non-solar, chemical reduction of CO_2 to CO or mixtures of CO_2/H_2O to syngas by oxidizing the lower valence metal oxide or metal; the cycle is completed by recycling the metal oxide back to the first step. The gaseous products can be further processed to liquid, hydrocarbon fuels by Fischer-Tropsch or other catalytic processes to produce carbon neutral solar fuels when the CO_2 is captured from the air.

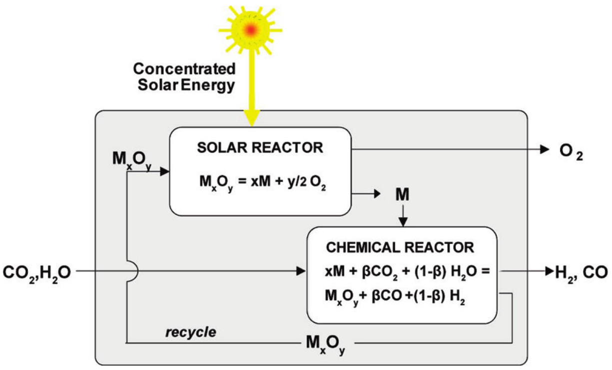

Figure 4 9. Schematic of the two-step H_2O/CO_2-splitting solar thermochemical cycle for syngas production with metal oxide redox reactions .

Purpose: The primary objective is to refine the science and develop the technologies for 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 2010: Chemical equilibrium compositions were examined with Gibbs free-energy minimizations for reactions of mixtures of CO_2 and H_2O with FeO and Zn as a function of temperature and pressure. Kinetic analyses with thermogravimetry were used to determine the reaction mechanism as mixtures of CO_2 and H_2O reacted with FeO and Zn to produce syngas and solid products of Fe_3O_4 and ZnO, respectively [4.16]-[4.18]. A Langmuir-Hinshelwood-type mechanism accurately described the competitive adsorption of CO_2 and H_2O on the solid surfaces. The chemical reduction of CO_2 to CO with Zn was demonstrated in an aerosol reactor [4.19].

Publications: [4.16]-[4.19]

Solar Thermochemical Dissociation of CO_2 and H_2O using Nonstoichiometric Ceria

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Funding:	NSF (USA), SNF (CH)
Duration:	July 1, 2009 – December 31, 2011

Background: Cerium oxide (ceria) has emerged as a highly attractive redox active material choice for two-step thermochemical cycling because it displays rapid fuel production kinetics and is highly selective. Using a solar cavity-receiver reactor, the oxygen uptake and release capacity of cerium oxide and the facile catalysis at elevated temperatures are combined to thermochemically dissociate CO_2 and H_2O, yielding CO and H_2, respectively.

Purpose: Demonstrate the feasibility of a solar-driven thermochemical cycle for dissociating H_2O and CO_2 using nonstoichiometric ceria in terms of materials, reaction rates, cyclability, reactor technology, and energy conversion efficiency.

Achievements in 2010: The two-step cycle consists of thermally reducing non-stoichiometric ceria at above 1770 K and re-oxidizing it with H_2O and CO_2 at below 1170 K to produce H_2 and CO, or syngas, the precursor

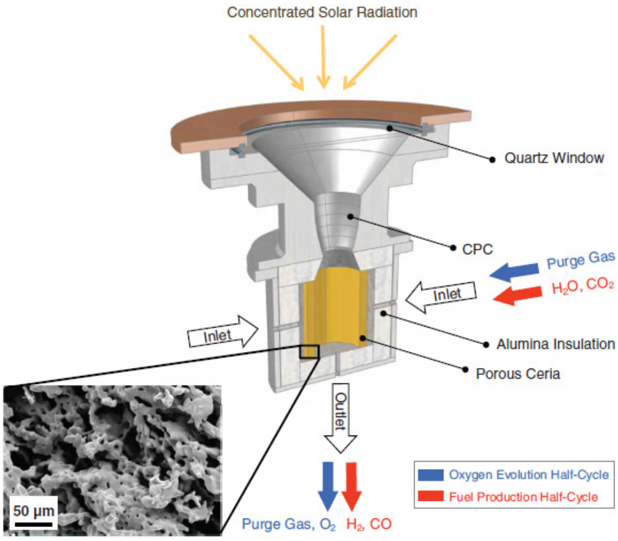

Figure 4 10. Schematic of solar reactor for two-step, solar-driven thermochemical production of fuels. The thermally insulated cavity receiver contains a porous monolithic ceria cylinder. Concentrated solar radiation enters through a windowed aperture and impinges on the ceria inner walls. Reacting gases flow radially across the porous ceria toward the cavity inside, whereas product gases exit the cavity through an axial outlet port at the bottom. Inset: Scanning electron micrograph of porous ceria tube after 23 cycles. Blue arrows indicate ceria reduction; red arrows indicate oxidation [4.21].

of liquid hydrocarbon fuels. High-rate solar fuel production from both CO_2 and H_2O has been demonstrated using a solar reactor (Figure 4 10) subjected directly to concentrated radiation in PSI's High-Flux Solar Simulator under realistic operating conditions relevant to large-scale industrial implementation, without the need for complex material microstructures and/or system design (e.g., additional quenching or separation steps). Rapid stable generation of fuel was demonstrated over 500 cycles. Solar-to-fuel efficiencies of 0.7 to 0.8% were achieved [4.20]. No heat recovery strategy was used. Both the efficiency and the cycling rates in the reactor were largely limited by thermal losses resulting from conductive and radiative heat transfer. A thermodynamic analysis of efficiency based solely on the material properties of CeO_2 indicates that 16 to 19% is attainable, even in the absence of sensible heat recovery [4.21]. Thus, with reactor optimization and system integration, substantial increases in both efficiency and fuel production rates are anticipated.

Publications: [4.20]-[4.21]

5-kW$_{th}$ Solar Demonstration of Ferrite Foam Device Reactor for Thermochemical Two-step Water Splitting

Participants:	Inha University, Sungkunkwan University (KOR), Korea Aerospace University
Contact:	Seo Taebeom, seotb@inha.ac.kr
Funding:	Korean Ministry of Knowledge Economy: € 396,932
Duration:	October 1, 2008 – July 31, 2011

Background: A major problem in the two-step thermochemical water-splitting cycle based on iron oxide redox pairs is the rapid deactivation of iron oxide particles in the cyclic reaction due to high-temperature melting and sintering. So far, the highly active, good repeatability of the cyclic two-step water-splitting cycle using iron-based oxide (ferrite) particles in a solar concentrator has still not been demonstrated.

Purpose: The objectives of this joint project between Niigata (J) and Inha (KOR) universities on the "Ferrite Foam Device Water-Splitting Reactor" are: (1) to develop reactive foam devices with ferrite as the working material, (2) to design and fabricate a windowed solar reactor with the reactive foam device, and (3) to demonstrate the reactor performance on sun with a 5-kW$_{th}$ dish-type solar concentrator.

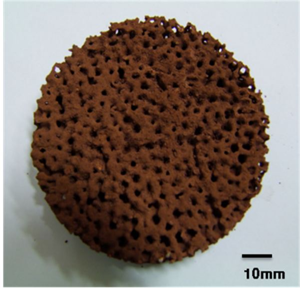

Figure 4 11. Photograph of $NiFe_2O_4$/m-ZrO_2-coated MPSZ foam.

Achievements in 2010: The reactive ferrite foam device, proposed and prepared by Niigata University (J), involves coating of inert zirconia foam with reactive ferrite-zirconia redox materials. In this project, the redox material was highly active $NiFe_2O_4$ supported on *m*-ZrO_2 ($NiFe_2O_4$/*m*-ZrO_2). A ceramic foam disk made of MgO partially-stabilized Zirconia (MPSZ) was coated with the $NiFe_2O_4$/*m*-ZrO_2 particles (Figure 4 11).

The two-step water-splitting cycle using the $NiFe_2O_4$/*m*-ZrO_2-coated MPSZ foam devices was demonstrated in the 5-kW$_{th}$ solar dish concentrator at Inha University in Incheon, Korea. The temperatures at the center of the foam device were 1470-1670 K for the thermal reduction (T-R) step and 970-1470 K for the subsequent water dissociation (W-D) step (Figure 4 12). Hydrogen was successfully produced during five cycles at a total amount of 878 Ncm^3 and ferrite conversion of 85% [4.22]-[4.23].

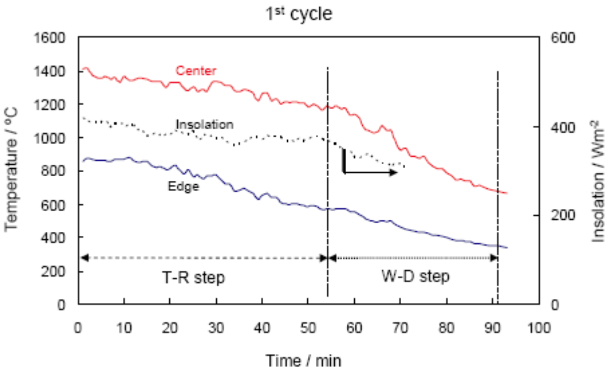

Figure 4 12. Time variation of temperature and insolation of the $NiFe_2O_4$/m-ZrO_2/MPSZ foam device during the 1st cycle (T-R step and W-D step).

Publications: [4.22]-[4.23]

HYDROSOL-3D – Scaling Up a Solar Monolithic Reactor for Thermochemical H_2 Production: A 3rd Generation Design Study

Participants: CERTH/CPERI (GR), DLR (D), CIEMAT (E), Total Gas & Power SA (F), HyGear BV (NL)
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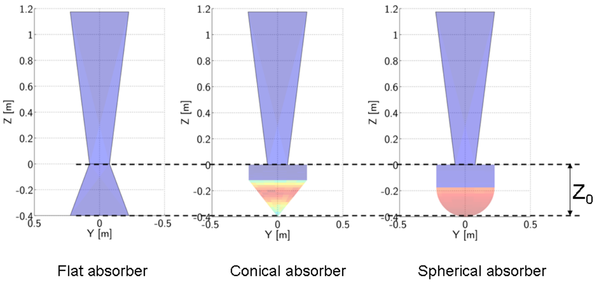
Christian Sattler, christian.sattler@dlr.de
Funding: Hydrogen and Fuel Cell Joint Undertaking
Duration: January 1, 2010 – December 31, 2012

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 scale, the current focus is on the preparation of a 1-MW solar demonstration plant, which is the next step towards commercialization.

Purpose: The main objective of HYDROSOL-3D is to (1) prepare a detailed design of a 1-MW demonstration plant for thermochemical H_2 production 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 of the regeneration step to considerably below 1500 K; (5) design the solar field control system with commercial solutions available from the market.

Achievements in 2010: Previously identified redox materials underwent stepwise modifications to fine-tune their composition with respect to high-temperature-tolerance characteristics such as resistance to sintering and vaporization, while at the same time securing constant high H_2 yield. The most promising candidate materials are being validated in an experimental campaign in DLR's High-Flux Solar Simulator.

The reactor design has been improved to significantly reduce reradiation losses, to finely homogenize the temperature distribution on the irradiated surface of the honeycomb structure, and to simplify maintenance and replacement of honeycombs. To this end, a secondary concentrator is being attached at the front of the receiver, and a spherical absorber is being made from a set of individual monoliths, which are supported by individual ceramic cups. A ray-tracing study helped to identify the most suitable geometry of the receiver and to design the secondary optics (Figure 4 13). Further, a reaction kinetics model has been developed to predict the reaction performance within the channels of the monolithic absorber.



Flat absorber Conical absorber Spherical absorber

Figure 4 13. Comparison of different reactor/absorber geometries optimized by ray-tracing analysis.

In parallel, the operating strategy was perfected, in particular, the timing of the process steps involved. Experimental series were carried out with the 100-kW_{th} pilot plant in the SSPS tower at the Plataforma Solar de Almería (PSA) to optimize half-cycle time, mass flows and feed stream composition [4.24].

Publications: [4.24]

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), ETH (CH), Empresarios Agrupados (E), BOOSTEC (F)
Contact: Martin Roeb, martin.roeb@dlr.de
Funding: EC (FP7), DLR
Duration: January 1, 2008 - March 31, 2011

Background: Solar energy is expected to play a major role in the production of future transportation fuels. In particular, solar thermochemical processes offer the potential of highly efficient massive hydrogen production at competitive costs. Although most of these processes have been evaluated in theoretical studies, the technology is not yet ready for application. Worldwide, the highest priority is currently given to the 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 for the key components. 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 1120 K and is one of the main foci of HycycleS [4.25].

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

Achievements in 2010: A prototype receiver-reactor for the decomposition of sulfuric acid (H_2SO_4) into SO_2 and O_2 has been intensively tested and simulated. It features a dual-chamber reactor for separate execution and examination of the H_2SO_4 vaporization and SO_3 reduction processes (Figure 4 14). The experimental operation at DLR's solar furnace in Cologne was successfully completed. Systematic test series included the variation of essential process parameters. Mean conversion of 40% was measured for an uncoated SiSiC foam absorber, while average conversion of 76% was measured for a honeycomb absorber coated with Fe_2O_3 catalyst. Reactor efficiencies higher than 40% were observed.

Computer tomography in conjunction with numerical techniques was used at ETH to determine the morphological characteristics of the SiSiC foam absorber of the solar H_2SO_4 evaporator. The continuum model for heat transfer and fluid flow was completed and used to derive effective transport properties – radiative characteristics, effective thermal conductivity, heat transfer coefficient, permeability, tortuosity –, which help identify the most suitable absorber structure [4.26].

A transient model for the SO_3 decomposer part of the reactor was developed and validated by using experimental data. A prototype compact heat exchanger as SO_3 decomposer has been designed, built and coupled to a heat loop where it is currently tested. The stability of construction materials for the decomposer and evaporator, as well as the activity of catalyst materials promoting the SO_3 reduction have been quantified in dedicated test rigs [4.27]

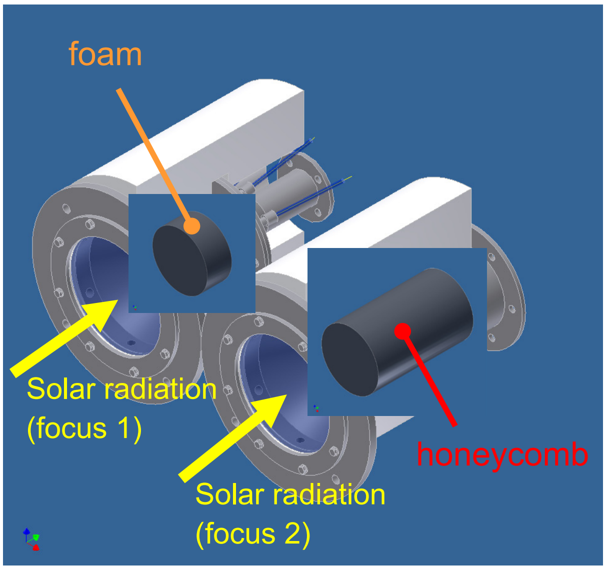


Figure 4 14. Scheme of volumetric receiver-reactor for sulfuric acid decomposition.

Publications: [4.25]-[4.27]

TEPSI – Innovative Technologies and Processes for Hydrogen Production Systems

Participants:	ENEA (I), Italian Universities (Roma La Sapienza, Politecnico di Milano, Roma III, Trento, Cagliari)
Contacts:	Pietro Tarquini, tarquini@enea.it
Funding:	Italian Ministry of Education, University and Research: € 3,500,000
Duration:	February 2006 – February 2010

Background: The TEPSI project is an initiative involving ENEA and several Italian Universities. Activities in past years concerned (1) the sulfur-iodine (SI) thermochemical cycle and (2) the manganese-ferrite (MF) thermochemical cycle for hydrogen production. Reactions requiring moderate temperatures, such as the Hydrogen-Iodide (HI) section within the SI cycle, may be powered by concentrated solar energy using parabolic troughs with ENEA's patented technology; reactions requiring high temperatures may be powered by solar towers, available through international cooperation with other countries (e.g., EU project HycycleS).

Purpose: The main purpose of the TEPSI project is to construct lab-scale plants for the production of about 10 normal liters (l_N) of H_2 per hour, in both the SI and MF cycles. Cost assessments for an industrial-scale SI hydrogen production plant are planned.

Achievements in 2010: The three subsections of the SI cycle (H_2SO_4 concentration and decomposition; HI purification and decomposition; Bunsen reaction for acid production) have been widely investigated before linking them together to realize a closed-loop cycle. In particular, a new procedure for phase separation and purification has been developed [4.28]. The HI decomposition reaction has been experimentally studied by feeding the reactor with both pure anhydrous HI and azeotropic water solution; the effect of possible impurities due to a non-complete species separation has been quantified [4.29].

The different sections of the SI cycle have been connected at ENEA's Casaccia Research Centre in a closed-loop plant operating at atmospheric pressure (Figure 4 15). The plant is made of quartz, pyrex, teflon and ceramics materials that are corrosion resistant to the HI aggressive environment. It has been checked for the best start-up conditions [4.30].

Figure 4 15. Testing performed in SI lab scale plant (10 l_N H_2 /h) at ENEA's Casaccia Research Centre, Italy.

Preliminary energy efficiency calculations and cost evaluations for an industrial solar SI plant show that the optimized version of the plant could produce H_2 at an estimated price of about 8.5 €/kg.

Publications: [4.28]-[4.30]

Solar Hydrogen Production by the Sodium Manganese Ferrite Water-Splitting Cycle

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Funding: TEPSI Project (01/2010-07/2010), ENEA, CNR
Duration: January 1, 2010 – January 31, 2012

Background: During the past five years, ENEA has extensively studied the sodium manganese ferrite water-splitting thermochemical cycle (until July 2010, this research was part of the national TEPSI project). It has been demonstrated that the $NaMn_{1/3}Fe_{2/3}O_2$ /$MnFe_2O_4$/Na_2CO_3/CO_2 system is able to cyclically produce H_2 and release O_2 at 1020 K [4.31].

Purpose: (1) Optimize the chemical efficiency of water-splitting and oxygen-releasing steps through the investigation and development of innovative materials with improved chemical reactivity for application in concentrated solar energy system; (2) Optimize the materials synthesis procedure and cycle operating conditions with regard to extended cycle performance and understanding the causes of aging; (3) Design, construct and test a reactor-receiver installed in a 1.5 kW facility for the on-sun demonstration of the cycle.

Achievements in 2010: A mechanism describing the sodium manganese ferrite transformation into manganese ferrite (oxygen releasing step) following sodium extraction by carbon dioxide has been proposed on the basis of a comparative analysis between thermal and in situ X-ray diffraction (XRD) analysis. Such experimental study enhances the comprehension of the chemical system under investigation and previously reported [4.32].

A laboratory setup has been realized with the scope of experimentally identifying the thermal quantities involved in the water-splitting reaction. The reaction enthalpy has been determined using a non-calorimetric method based on the van't Hoff equation [4.33].

Developed materials (porous pellets) have proved to produce H_2 for 30 hours without significant degradation (Figure 4 16).

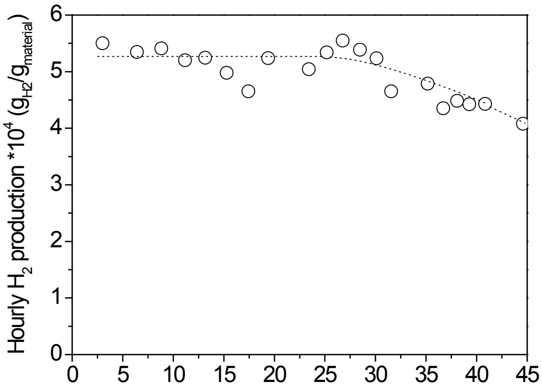

Figure 4 16. Hourly H_2 production as a function of materials aging during the production stage. Noticeable decrease in materials activity is observed after 30 hours.

Furthermore, a receiver-reactor made of inconel alloy has been designed and constructed, and is currently being validated.

Publications: [4.31]-[4.33]

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

Participants: Hynergreen Technologies S.A. (E), IMDEA Energía (E), CIEMAT (E), CIDAUT (E), University Rey Juan Carlos I Madrid (E)
Contacts: Victoria Gallardo, victoria.gallardo@hynergreen.abengoa.com
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 20 solar R&D institutions including reputed Spanish companies and the most prestigious technological centers. The overall project goal is enhancement of various high-concentration solar thermal technologies.

Purpose: Within the "Solar Hydrogen" activity, the program of work aims to investigate the incorporation of high-temperature thermochemical cycles for solar 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.

Achievements in 2010: 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 activity of commercially available ferrites with various compositions has been previously evaluated with respect to ferrites synthesized in the laboratory by different preparation methods.

Ferrites substituted with different metals (Ni, Co, Mn) have been prepared by the co-precipitation method using NaOH as precipitation agent (Figure 4 17). Thermochemical cycles assayed in a laboratory test bench demonstrate that all these synthetic ferrites are able to split water in two steps, even if they are subjected to a second cycle. Among the samples studied, $CoFe_2O_4$ appears as the most promising material for H_2 production (42.7 Ncm^3/g after two thermochemical cycles), showing more activity than any other ferrite previously evaluated. In addition, a synthetic Ni ferrite presented in this work exhibits the same H_2 production characteristics as a commercial ferrite studied previously [4.34].

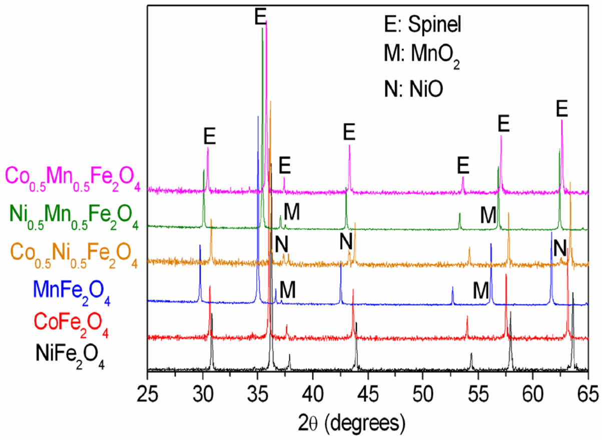

Figure 4 17. XRD patterns of several synthetic ferrites under investigation.

Publication: [4.34]

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

Participant: CIEMAT (E)
Contact: Alfonso Vidal, alfonso.vidal@ciemat.es
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 addresses major technology investments in the CRS-SSPS solar tower test facility, to or to offer unique research services to users from other countries (Figure 4 18).

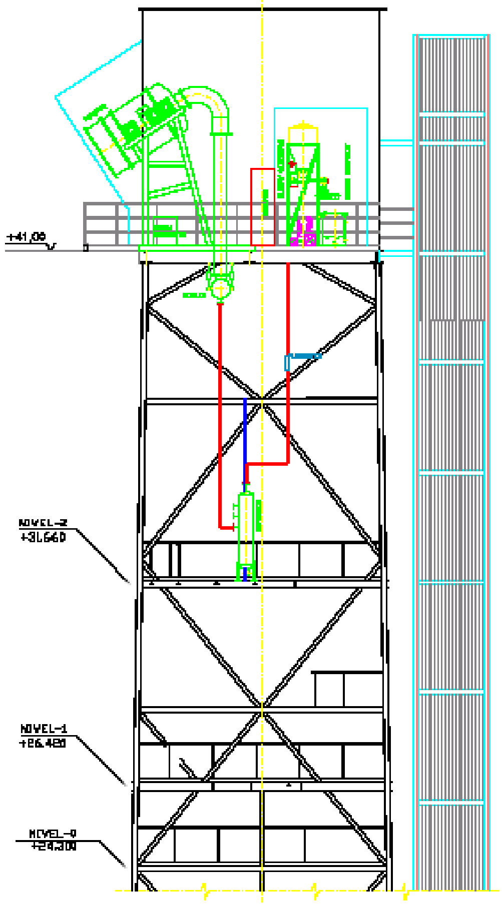

Figure 4 18. Schematic layout of the CRS-SSPS plant at PSA, Spain.

Most important investments include equipment for a suitable test-bed for this user-lab activity: optimized coolers for increasing cooling tower capacity; supply of water, air, and nitrogen; optical fiber communication; improved control tools, such as supervisory control and data acquisition (SCADA) software; torch for burning off-gas; flow meters, etc. At present, the CRS-SSPS solar tower accommodates two important solar thermochemical H_2 and syngas production projects (HYDROSOL-3D and SYNPET).

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 (SRB), SIRMIUM (SRB), D'Appolonia S.p.A. (I), Termolan s.r.l. (I), Lindbergh Trading (Pty) Limited (ZA)
Contacts:	Michael Epstein, michael.epstein@weizmann.ac.il Aldo Steinfeld, aldo.steinfeld@eth.ch
Funding:	EC funded project, cost shared: € 4,950,000
Duration:	June 2010 - May 31, 2014

Background: Primary aluminum production industry is the world's larger industrial consumer of energy and among the most CO_2 intensive industries. It also discharges enormous quantities of wastes that further decrease the exergy efficiency of its production process. The conventional production of aluminum via the Hall-Héroult electrolytic process is characterized by its high energy consumption – approximately 45 GJ/ton Al – and its associated high specific greenhouse gas emissions – 7.4 ton $CO_{2\text{-equiv}}$/ton Al.

Purpose: (1) Demonstration and validation, at industrial scale, of novel, energy-efficient, environmental-friendly and cost-effective technologies for the reduction of alumina to aluminum, based on the carbothermic reduction process. Two different technologies will be investigated: (i) high temperature carbothermic reduction in an electric arc furnace and (ii) moderate temperature carbothermic reduction in a novel solar furnace; (2) Demonstration and validation, at industrial scale, of an innovative, energy-efficient and environmental-friendly technology for 100% utilization of bauxite residue (red mud) produced in the Bayer process; (3) Site optimization study of the new primary aluminum industry, integrating the proposed technologies.

Achievements in 2010: Thermochemical equilibrium calculations indicate the possibility of significantly lowering the onset temperature of aluminum vapor formation via carbothermal reduction of Al_2O_3 by decreasing the total pressure, enabling its vacuum distillation. Further, the formation of gaseous Al should occur without the accompanying formation of Al_2O, Al_4C_3, and Al-oxycarbides. Alternatively, liquid Al can be produced by operating at high temperature with excess of carbon, thereby again avoiding carbide and sub-oxide formation. The implementation of such carbothermic reduction processes in the aluminum production could lead to energy savings of up to 16%, GHG emissions reductions of up to 32%, and exergy efficiency increase of up to 5%. Additionally, the prospect of utilizing concentrated solar energy to provide process heat can render the primary aluminum production truly sustainable. When the reducing agent is derived from a biomass source, the solar-driven carbothermal reduction is CO_2 neutral.

Exploratory experimental runs using a solar reactor (Figure 4 19) were carried out at temperatures in the range 1300-2000 K and total pressures of 3.5-12 millibar, with reactants Al_2O_3 and bio-charcoal directly exposed to simulated high-flux solar irradiation [4.35]. Aluminum was recovered by condensation of product gases, accompanied by the formation of Al_4C_3 and Al_4O_4C within the crucible. Based on the measured CO generation, integrated over the duration of the experimental run, the reaction extent reached 55% at 2000 K.

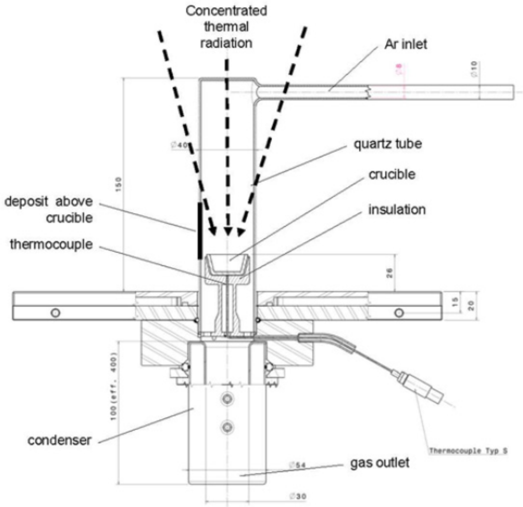

Figure 4 19. Vacuum solar reactor featuring a quartz tube containing a glassy carbon crucible with reactants directly exposed to concentrated solar radiation. From [4.35].

Publications: [4.35]

4.3 Publications

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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 Task III Objectives for 2011

In the context of growing commercial CSP project activities, further development and improvement of all CSP plant components is an obvious Task III challenge. The findings of studies like ECOSTAR on the impact of technology R&D on final CSP plant cost reduction should be borne in mind and refined to efficiently allocate R&D funds to the most promising topics.

As our industrial partners competitively pursue project development and R&D on component development, the following activities appear to be appropriate for supportive collaboration, moving the technology forward:

- **Guidelines for component performance measurement**, which can help component suppliers and plant operators qualify and validate their specifications. Here, SolarPACES working groups consisting of R&D organization together with industry partners are sharing their knowledge on appropriate measurement procedures and develop suited guidelines which are shared with standardization organizations.
- **Prioritization of R&D activities with high impact on cost reduction.** The findings of studies like Ecostar on the impact of technology R&D on reduction in the final cost of CSP plants will be further refined. In addition, SolarPACES Task III will work as a catalyst in setting up international R&D projects by leveraging funds to follow the roadmap laid out.
- **Reliability Evaluation of solar components and systems**. SolarPACES Task III will develop methods and procedures for predicting the life-time performance of solar plant components and systems. This also includes the development of methods for long-term stability testing (e.g., accelerated aging procedures).
- **Concentrator system quality assurance tools and methods**, to assure the optical quality of concentrators during installation and operation, including fast measuring systems for internationally standardized concentrator quality control and component performance characterization, including harmonization of simulation tools to offer investors reliable product and performance data.
- **Improvement of the quality and capacity of testing facilities.** The aim is to ensure proper testing capabilities in all SolarPACES Member countries by setting common quality standards and foster facility improvements.
- **Comparison and evaluation of storage concepts** Define a methodology for comparing and assessing storage concepts and collecting design and operation data from systems under testing in different locations
- **Power plant optimization for arid regions.** SolarPACES TaskIII will analyze options to operate solar thermal power plants efficiently at sites with low water availability. This analysis will be based on experience in conventional power plant operation under dry cooling conditions.

Reported Task III Activities in 2010 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).

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	Reflector Shape Analysis	Eckhard Luepfert				
	Fast 3D optical profilometer for the shape measurement of pa	Marco Montecchi	x			
	New techniques for solar field maintenance in parabolic trough	Javier Bezares	x			
	Optical alignment of parabolic trough modules	Marco Montecchi	x			
Tower	Solar hybrid power and cogeneration plants (SOLHYCO)	Peter Heller		x		
	A Novel Pressurized Air Receiver for Solar-driven Gas Turbines	Illias Hischier	x			
Dish	Dish Engine Development	Chuck Andraka	x			
Storage	Optimization of thermal storage components and equipment	Esther Rojas	x			
	Supporting Tools and Test Facilities					
	SFERA: Solar Facilities for the European Research Area	Diego Martinez	x	x		
	QUARZ Test and Qualification Center for CSP Technologies	Björn Schiricke	x			
	Test Facility for Solar Driven Expansion Machines, Thermal Energy Storage, Absorbtion Chillers and Desalination Units	Anton Neuhaeuser	x			
	Digital Solar Atlas for Kingdom Saudi Arabia	Christoph Schillings	x			
	Development and qualification of a new parabolic trough collector	Mauro Miotto	x			
	Detailed optical characterization of solar mirrors	Anna Heimsath	x			
	Measuring Temperatures in a High Concentration Solar Simulator – Demonstration of the Principle	Ivo Alxneit	x			
	Development of a Spatially-Resolved-Reflectometer SpaceRR	Florian Sutter	x			
	Advanced Technologies and Applications					
	Largest Solar Cooling System in the Middle East for a Showcase Football Stadium in Qatar	Christian Zahler	x			
	Durability of reflector materials	Aránzazu Fernández García	x	x		
	Standards for CSP components					
	Development of guidelines for standards for CSP components	Peter Heller	x			
	Solar weighted direct reflectance measurement for solar mirrors	Stephanie Meyen	x			

5.3 Summary of Achievements in 2010

5.3.1 Components and subsystems

5.3.1.1 TROUGH

Reflector Shape Analysis

Contacts: Eckhard Lüpfert, e.luepfert@dlr.de
Steffen Ulmer, steffen.ulmer@dlr.de
Participants: DLR, Ciemat, NREL, SANDIA, ENEA, industrial partners
Funding: several sources

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 called the “intercept factor” (IF). The intercept factor depends on the reflector geometry as well as on geometric parameters of the receiver (size, position) and on 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 the parameters influencing the intercept factor. In previous work performed at the majority of CSP development institutions, 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. The first two methods have therefore proven most practical for finding the orientation of the reflection on the mirror itself. Successful examples are the DLR’s QDec, NREL’s AIMFAST and SANDIA’s TOP and VShot methods, as well as laser reflection measurements applied by ENEA, Flabeg, and others.

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

- Increasing and maintaining mirror quality and CSP power plant output, and
- Enhancing development of new competitive materials, products and suppliers.

Slope measurement accuracy required for CSP mirrors is 0.2-2 mrad. For successful measurements, not only the appropriate methods are required, but also 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 under different boundary conditions to achieve comparable evaluations.

Based on measurement results and ray-tracing analyses it has been proposed that mirror shape quality be specified with the standard slope deviation parameters SDx and SDy, and standard focus deviation FDx and FDy in transversal and longitudinal directions respectively. 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 much more significant as quality parameters for a key CSP technology component.

The target for high-performance trough collector glass reflectors is a standard slope deviation SDx of 1.5-2.5 mrad, and for the standard focus deviation FDx in transversal direction about 15% of the absorber diameter.

Minimum specification of RP3 mirror panels should meet FDx below 12 mm. Current state of the art for the standard focus deviation in RP3 mirror production is under 10 mm, and relevant potential is 8 mm or even less, with relevant impact on the solar field performance. A

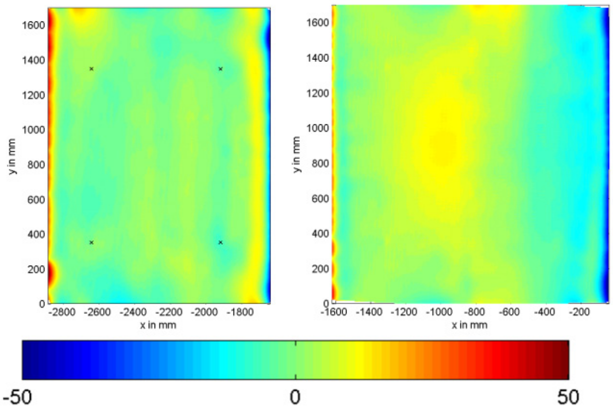

Figure 5.1 Example of a QDec measurement of the spatial distribution of the transversal focal deviation (FDx) for the surface analysis of a pair of mirrors (RP3 inner and outer), scale in mm

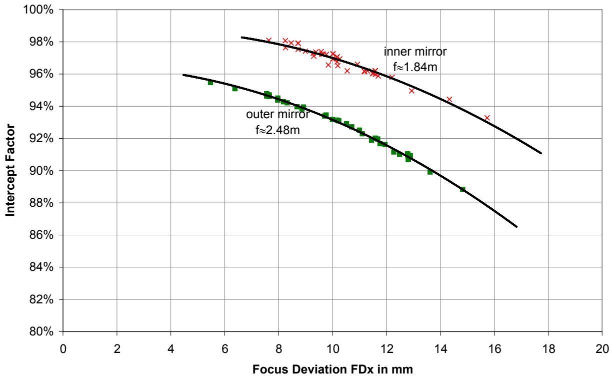

Figure 5.2 Sun intercept factor - ray-tracing results for EuroTrough (RP3) mirror panels assuming a typical sun-shape and including typical tolerances for the rest of the collector components, for 0° incidence angle

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 producers as well as for solar field assembly quality control.

Publications:

[5.1] E. Lüpfert, S. Ulmer: Solar Trough Mirror Shape Specifications, Solarpaces Conference, Berlin, September 2009

Optical alignment of parabolic trough modules

Contact: Marco Montecchi, marco.montecchi@enea.it
Participants: ENEA

Future diffusion of concentrating solar power (CSP) technology strongly depends on the plant cost, which is certainly related to solar-radiation concentration efficiency of the heat collection element (HCE). Although structural design and installation procedure are both conceived to ensure good efficiency right from assembly, suitable methods and instruments for in-situ confirmation of its optical alignment are required. In particular, parabolic-trough drafts, it must be checked that: 1) the HCE is set according to the torque tube and 2) the facet mirrors are correctly shaped and aligned to ensure a satisfactory intercept factor (IF). If compliance is insufficient, precise instructions for fixing the problem simply have to be quickly available.

For the first, we tested a number of different techniques, and finally found the simple optical sighting method to be the most reliable. Both ends of the HCE unit must be visible simultaneously, from the same point of view, when sighted along one of the two inner mirror facet edges. Otherwise the HCE supports have to be adjusted until that is accomplished. Initially we used an old theodolite, but with experience, we found that simple binoculars work just as well.

For the second, a new instrument called the VISfield (Visual Inspection System field version) was developed based on ray reversibility (Helmholtz's theorem). The intercept factor is given by the portion of the expected size of a hypothetical solar spot on the HCE overlapping the image of the receiver itself (reflected by the mirror). Moreover, the slope deviation from an ideal parabola is evaluated by the displacement of the HCE image from the expected position.

Fig. Figure 5.3 shows the VISfield. A fireWire camera is mounted on a translational rail installed on a flatbed trailer. The VISfield inspects the lower half of the parabolic-trough module (12 m) directed at the horizon for about 2 minutes and outputs: 1) intercept-factor (IF) map and average for each facet at the working solar-declination of the plant; 2) adjustments at the facet attachment point to improve the IF; 3) after optimization, facet-mirror compliance by means of its IF (map and average). Further details are provided in [1].

The VISfield is manufactured and marketed by Marposs under ENEA license.

Figure 5.3 First Marposs VISfield prototype.

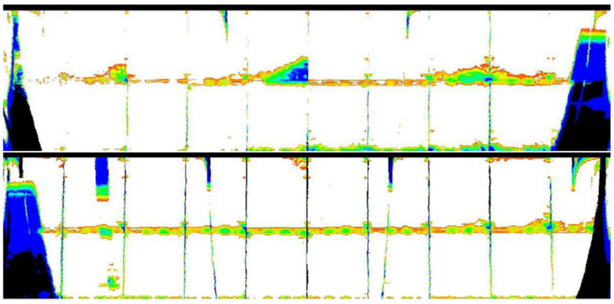

Figure 5.4 Intercept-factor color map of a 12-m long module (white IF=1, …., blue IF<0.1; black = no HCE image).

Publications:

[5.2] M. Montecchi, A. Benedetti, G. Cara, *Optical alignment of parabolic trough modules,* Poster 107 at SolarPACES 2010.

New techniques for solar field maintenance in parabolic-trough collector plants

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Marta Nebreda, martanebreda@bcb.es
Participants: BCB Informática y Control

BCB Informática y Control is an engineering company with over 14 years experience in machine vision, thermography, data acquisition, automation and control and ATE (Automatic Test Equipment). BCB offers its customized solutions for the control and management of industrial processes, providing added value to help them becoming more competitive and produce energy more efficiently.

For the solar industry, mainly parabolic-trough collector technology, BCB offers a package of highly varied products and services aimed primarily at operation and maintenance, and focused on optimizing and automating industrialization. BCB makes use of its unique experience gained in over ten years in the automotive industry and five working in the construction of the world's first commercial solar thermal power tower plants (PS-10 and PS-20 of Abengoa Solar).

BCB is working on developing new products and services based on predictive maintenance (such as non-destructive testing with machine vision using IR cameras and multiple sensors), preventive maintenance (with the data acquisition and periodic analysis) and corrective maintenance (involving repairs and corrections of errors or defects), in order to meet the needs identified in this sector.

Portable detector for solidified HTF inside pipes.

Thermal fluids such as oil or salts solidify at 12ºC and 233ºC, respectively, inside the lagging pipe (6" to 30") and the metal tube inside the absorber tubes. This device provides reliable detection of frozen areas.

Gas leak detector for fire prevention.

To prevent fires caused by problems in the ball-joints, early detection of hydrocarbon gas leaks by IR thermography (MWIR and LWIR) is necessary.

Fire detection.

The system is based on IR cameras that detect hot spots. Image processing is important to reduce false errors (during the day) caused by glare (the temperature of the Sun's surface is 5800 K).

On-line analysis of thermal oil quality.

Using the spectral characteristics of each compound, it is possible to detect the subproducts generated by oil degradation (when it reaches temperatures higher than 400 ºC). This can occur when there has not been possible to blur a collector and oil is not circulated because the presence of a stopper.

Inspection of the solar field using a vehicle with instrumentation on board.

A vehicle with the appropriate instrumentation travelling through the solar field can automatically collect and analyze data and generate reports on the actual state of the solar field day (visible and IR cameras) or night (IR camera) for use in maintenance.

The vehicle is equipped instrumentation including two IR cameras, one working in the LWIR for checking thermal insulation (vacuum) and detecting leaks, and the second one working in the SWIR with a filter wheel to measure the outer surface temperature of the collector tube (on the surface of the glass) and the surface temperature of the metal inner tube (very close to the oil temperature). Another visible camera checks getter state and tube geometry (buckling and concentricity).

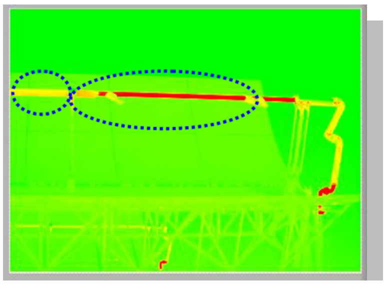

Figure 5.5 Thermographic image of a broken tube in a trough.

Cloud cover modeling to calculate real-time shadows on the solar plant.

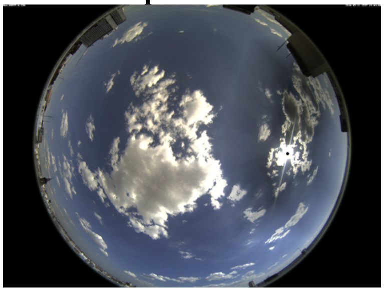

Figure 5.6 Hemispheric image. Cloud cover for 3D modelling.

Using hemispheric cameras and stereoscopic vision, it is possible to model plant cloud cover. This calculates the shadows over the solar field in real-time, which assists in plant operation and making the necessary control decisions.

Portable equipment for dimensional control in the solar field.

BCB Shape equipment is based on a digital caliper and an ultraportable computer. It allows exhaustive, agile control of any piece (with its AutoCAD drawing) involved in the construction of the thermal plant, automatic storage of the information acquired and report generation, ensuring full traceability and detection of the parts that do not meet the dimensional standards set.

Fast 3D optical profilometer for the shape measurement of parabolic-trough reflective-panels

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Participants: ENEA

The effectiveness of a solar concentrator strongly depends on the accuracy of the shape of its reflective panels (facets). ENEA has developed a high-precision optical profilometer [1] for in-laboratory characterization which was intensely used for parabolic-trough reflective panel R&D by several Italian producers. The instrument measures the panel surface in terms of x,y,z coordinates and the derivatives $\partial z/\partial x$ and $\partial z/\partial y$. Then a number of figures (the most representative being the intercept factor) are evaluated by means of ray tracing. The results are essential to optimize the manufacturing process. Unfortunately this instrument is not suitable for industrial quality control because of the measuring time, which is quite long (about $1h/m^2$).

Based on the Visual Inspection Method [2], a totally new 3D optical profilometer named VISprofile was developed. The new instrument is composed of: i) a linear array of point light sources; ii) a FireWire camera; iii) a translational rail. The linear source array is placed along the focus; the camera is installed on the translational rail, which is placed about 6 m in front of the parabolic-trough panel, parallel to its axis. The rail is about 20% longer than the axis. The camera lens is set so that it can frame the entire width of the parabolic-trough panel along the flat direction. The length of the point source array is set to

Figure 5.7 VISprofile. The linear array of point light sources is placed along the focus of a parabolic-trough panel. On the left, not shown, the camera is installed on the translational rail.

allow the image to be viewed across the entire panel width. A number of frames are shot by moving the camera into different positions. This way, the range covered is wide enough to see the image of the source array spanning the whole panel surface during the scan. Coordinates and derivatives of the surface are calculated by the laws of reflection, given the positions of the point sources, their images and the camera. Afterwards, the panel features are evaluated with the same software as the older profilometer [1]. Measurement and analysis of a panel shaped like half a parabolic-trough (3 m axis) with resolution of 1 point/cm^2 takes about 2 min. The accuracy on profile and derivatives is better than 70 µm and 50 µrad, respectively.

The VISprofile and the old optical profilometer [5.3] are arranged to share the same sample holder for rigorous cross-checking. The results achieved with these two instruments on the same panel are in very good agreement.

The VISprofile is fast and robust enough to be used for industrial quality control. The instrument is now being marketed by Marposs under ENEA license.

Publications:

[5.3] A. Maccari, M. Montecchi, An optical profilometer for the characterisation of parabolic trough solar concentrators, Solar Energy 81 (2007) 185-194.

[5.4] Italian patent deposited on March 3rd, 2008,N o RM2008A000151.

Development and qualification of a new parabolic trough collector

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Participants: D.D. Srl (I), ENEA (I)

Located in the northeast of Italy, D.D. Srl is involved in design, production and assembly of solar thermal plants since 2001 (ENEA's PCS molten salt experimental plant), focusing on parabolic-trough collector supporting structure and tracking system. In 2009-2010, D.D. Srl developed with ENEA support, innovative CSP collector solutions to improve parabolic trough features, precision and efficiency. The solutions have been jointly patented by D.D. and ENEA. Research goals mainly focused on:

- Cost reduction targets. Hardware designed for standardized manufacturing and modular assembling, keeping down costs and smoothing out construction. Permanently low maintenance needs.
- Optimizing system reliability and fast maintainability in a challenging context. Guaranteeing lifetime optical efficiency in a parabolic trough conceived for molten salt operation (wide temperature range), taking into account thermal and wind effects, but also maintenance needs (e.g., precision after partial disassembly or part replacement), reduction of skilled labor during plant erection, and exposure of latent errors. Tracking system: testing long term durability at any wind load torque.

With these requirements, D.D. developed and tested:

- New support frame philosophy (developed and patented with ENEA): a main cylindrical beam supports lightweight centering-ribs to which the reflective panels are individually attached, suitable for all mirror types.
- Advanced features: the entire structure is a single holding machine, all reference interfaces have CNC machine tolerances, no adjustment is required, design precision is achieved without need of reworking, and insensitive to assembly order, parts replacement, and human error.
- Special friction-free bearing-type supports (D.D. patent), axially free to compensate movement, hermetically sealed, life-lubricated.
- New tracking system (D.D. patent): electromechanical drive with automatic clearance compensation system, high-precision continuous movement, fully sealed, self-lubricated and maintenance-free, low energy consumption.

Cost reduction is achieved by focusing on plant construction, operation, and maintenance. Since our procedure assures high-precision component manufacture, performance of every module is highly repeatable. The structure does not need any adjustment, since design precision is achieved during manufacturing. That means fast, error-proof assembling, reliable part replacement, ready precision establishment. Furthermore, components are designed for manufacturing (DFM) and are ready to be flexibly industrialized, keeping costs down.

Tests by ENEA have covered both structure and drive on D.D. experimental plant (Fig.1), proving better performances in comparison with technical specifications. After checking the entire structure, mirror joins showed a max misalignment (laser total station data vs ideal profile) of 2 mm and a consequent structure angular deviation <0.8 mrad. Intercept factor measured using the ENEA Visual Inspection System reached 0.98.

Tracking testing system comprises two lifting drums (Fig.2), the employment of 5 and 10 tons steel loads, a clock based controls to compare input ideal and output real position. While accuracy is measured under tracking mode, accelerate aging is performed at max speed. D.D. drive has also been successfully tested for 10500 cycles (36 equivalent years), simulating wind load torque of 27 kNm (24% of total cycles, wind@7 m/s), 54 kNm (71%, w@9 m/s), 100 kNm (4.5%, w@10 m/s) and 130 kNm (0.5%, w@28 m/s). Gear has shown no signs of wear or tear. The movement has been assured on the entire range (0-130 kNm) and reaches 1720 mrad/min max speed at any load. Sun tracking accuracy has achieved an error <0.17 mrad in 94% of the total position points, holding this precision at any wind load, in the entire 36 year simulation. On tracking mode, electric power consumption is limited from 140 W (27 kNm load) to 210 W (54 kNm).

Figure 5.8 D.D. collector: experimental modules

Figure 5.9 D.D. tracking drive: testing drums

5.3.1.2 Tower

Solar hybrid power and cogeneration plants (SOLHYCO)

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Participants: DLR (D), Turbec (S), CEA (F), Ciemat (E), Solucar (E), Ormat (I), GEA (POL), NEAL (ALG), FUSP (BRA), Vitalux (BRA), IIE (MEX)
Funding: EC FP6 STREP; 3.4 M€ total cost, duration 54 months

The SOLHYCO project was completed in June 2010. It focused on the development of a prototype solar-hybrid microturbine conversion system for cogeneration. The unit power is 100kW$_e$. The main innovations in the project were:

- Development of a solar-hybrid microturbine prototype unit based on a commercial microturbine
- Development of a new high-performance tube technology for solar receivers
- Development of a bio-fuel combustion system able to operate with bio-fuels

Figure 5.10 Operation of the Solhyco prototype system in the CESA-1 tower

In 2010 the new microturbine prototype system continued to be operated in the CESA-1 test facility at the Plataforma Solar de Almería. By the end of the test period, more than 100 hours of solar-hybrid operation had been accumulated. The solar receiver was able to deliver solar heated air at 800°C to the microturbine. The commercial turbine control system had to be adapted to the different characteristics of the solar-hybrid system. The start-up of such a system is especially complicated due to the additional air volume and heat sink in the receiver. Nevertheless during the test phase, all operating modes could be demonstrated successfully and the system behaved very well.

The solar receiver was a cavity type tubular receiver with an open aperture. In the last stage of testing, the receiver aperture was covered with a quartz window which resulted in a significant increase in efficiency. However, due to problems with shrinking of the ceramic insulation material in the cavity housing, precise verification of complete system efficiency could not be achieved.

The detailed final project report can be found at www.solhyco.com.

It is planned to replace the cavity in an upcoming project and continue operation and performancee measurement of this prototype system.

A Novel Pressurized Air Receiver for Solar-driven Gas Turbines

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Participants: ALSTOM, ETH Zurich, PSI

CSP's dish and tower technologies can achieve solar concentration ratios exceeding 2000 suns, and therefore, supply solar process heat at above 1000°C.directly to the topping Brayton cycle of a combined cycle power generation. The key component of such a solar-driven combined cycle (SCC) is the solar receiver, where concentrated solar thermal energy is absorbed and transferred to the pressurized air or any other working fluid expanded in the gas turbine. The receiver requirements for a SCC are defined by the inlet conditions of the gas turbine, i.e. temperatures in the range 1000–1400°C and pressures in the range 8–30 bars.

A novel design of an indirectly-irradiated solar receiver is shown schematically in **¡Error! No se encuentra el origen de la referencia.**. It consists of an annular reticulate porous ceramic foam (RPC) bounded by two concentric cylinders. The inner cylinder has a small aperture to let in concentrated solar energy. Because of its cavity-type configuration, it can capture efficiently incoming radiation that undergoes multiple internal reflections. A 3D-CPC is incorporated at the aperture to boost the solar concentration ratio and reduce the aperture size and re-radiation losses. Absorbed radiant heat is transferred by conduction, radiation, and convection to the pressurized air flowing across the RPC. The outer cylinder is made of non-porous insulating material and is surrounded by a metallic shell to maintain the inner pressure of 10 bars.

This solar receiver design offers several intriguing advantage: 1) high apparent absorptivity due to cavity-type geometry; 2) high convective heat transfer from the RPC to air; 3) homogeneous and monotonously increasing temperature profile; 4) uniform compressive load on the cavity; 5) reduced re-radiation losses at the cavity inlet due to entering cold air; and 6) scalability as single or as multi-receiver array. The disadvantages are those common to indirectly-irradiated receiver concepts, i.e. the limitation associated to the thermal transport properties of the materials of construction. Candidate materials for the cylindrical cavity and RPC are ceramics (SiC, Al_2O_3) and high-temperature metallic alloys.

The governing steady-state mass, momentum and energy conservation equations were formulated and solved numerically by coupled Finite Volume and Monte Carlo techniques. Validation was accomplished with experimental results using a 3 kW solar receiver prototype subjected to average solar radiative fluxes in the range 1870 – 4360 kW m^{-2} (see adjacent figure). Experimentation was carried out with air and helium as working fluids, heated from ambient temperature up to 1335 K at an absolute operating pressure of 5 bar. The validated model was then applied to optimize the receiver design for maximum solar energy conversion efficiency (exceeding 90%) and to analyze thermal performance of 100 kW and 1 MW scaled-up versions of the solar receiver.

Publications:

[5.5] Hischier I., Hess D., Lipinski W., Modest M., Steinfeld A., "Heat Transfer Analysis of a Novel Pressurized Air Receiver for Concentrated Solar Power via Combined Cycles," *J. Thermal Sci. Eng. Appl.*, **1**(4), pp. 041002-6, 2009.

[5.6] Haussener S., Coray P., Lipinski W., Wyss P., Steinfeld A., "Tomography-Based Heat and Mass Transfer Characterization of Reticulate Porous Ceramics for High-Temperature Processing", *J. of Heat Transfer*, 132, pp. 023305 1-9, 2010.

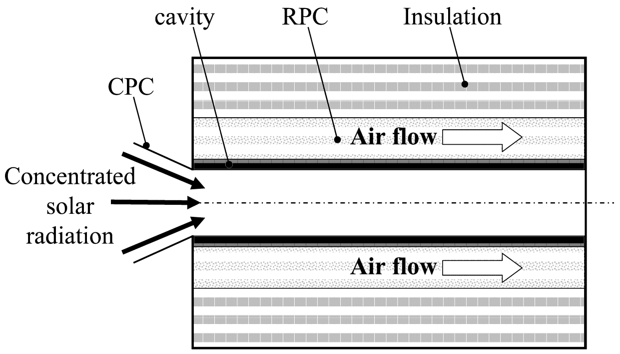

Figure 5.11 Solar receiver concept featuring an annular reticulate porous ceramic foam (RPC) bounded by two concentric cylinders. Concentrated solar radiation absorbed by the inner cylindrical cavity is transferred by conduction, radiation, and convection to the pressurized air flowing across the RPC.

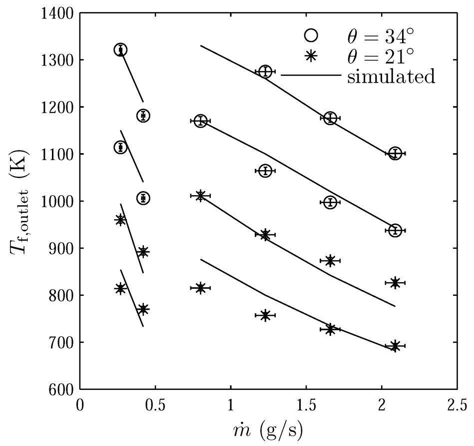

Figure 5.12 Experimentally measured (dots) and numerically simulated (solid lines) fluid outlet as a function of the mass flow rate.

5.3.1.3 Dish

Dish Engine Development

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Participants: Sandia National Laboratories; Stirling Energy Systems; Infinia Corp; Brayton Energy; Southwest Solar
Funding: DOE and private

Dish engine point focus systems continue to hold promise of low cost energy production through high efficiency operation. Several US firms are developing dish engine systems for production deployment. Stirling Energy Systems and Infinia are making significant strides toward commercialization of dish Stirling systems. Brayton Energy and Southwest Solar have teamed to develop a dish Brayton system with compressed air storage.

Stirling Energy Systems completed construction and operated a 60-dish plant near Phoenix AZ. Each dish has 25kW rated output, for a total of 1.5 MW. SES operated over the first half year with over 97% availability. They continued product development and improvement, with developmental testing at the 10-dish installation at Sandia National Laboratories in Albuquerque NM. Improvements identified and demonstrated at Sandia were then deployed at Maricopa.

Infinia Corporation completed its first 30-unit commercial installation of their PowerDish™ in Yuma, AZ in August 2010. Infinia has other utility-scale projects in the US, Europe and India following soon after the dairy processing facility project in Yuma with full production launch in 2011. 100 pre-production and test units are currently operating at ten different sites around the world. The 3.2 kW (STC DC equivalent of 3.83 kW) PowerDish is 24% efficient and enables scalable power solutions from kilowatts to 100s of megawatts for commercial, industrial, and utility-scale applications. Each PowerDish has a service life that exceeds 25 years. To enable high-volume, low-cost production of the PowerDish, Infinia has partnered with large Tier 1 automotive component manufacturers and suppliers.

Figure 5.15 SouthWest Solar Technology dish with Brayton Energy PCU

Brayton Energy and Southwest Solar Technologies are developing a dish Brayton system, with support of the DOE for engine development and solarization. The dish has a 320 m^2 aperture, and in solar-only mode will provide 80 kW net electrical output. Brayton is also pursuing a novel turbine-only version that uses Compressed Air Energy Storage to store low-cost nighttime electrical energy as compressed air. A protoype dish has been erected near Phoenix AZ, and system testing is anticipated in 2011.

Figure 5.13 SES Maricopa 60-dish plant in operation near Phoenix, AZ

Figure 5.14 34 Infinia Corporation dish Stirling systems in operation at Yuma AZ

5.3.1.4 Storage

Optimization of thermal storage components and equipment

Contact: Esther Rojas, esther.rojas@ciemat.es
Participants: CIEMAT, Spanish/ European companies

The European Commission Technology Roadmap 2010-2020 established four technology objectives for Concentrated Solar Power, one of which is the improvement of operational flexibility and energy dispatchability either by developing and improving energy storage or by hybridization. Aligned with this approach, Ciemat, by its Concentrating Solar Systems Unit, is been working on developing and optimizing thermal energy storage systems since several years. Today there are two main R&D lines related to thermal storage development:

(a) Components design and optimization:

Knowing that one of the main drawbacks to have an economic latent storage system is the low thermal conductivity of the common storage media used as phase change materials (inorganic salts) and that a way to solve it is by an adequate design of the storage unit, an exhaustive review of applicable heat exchanger designs, related research projects, patents and papers have been carried out. As a result a new concept design for a latent heat storage module has come out and will be developed in the future.

In sensible heat storage systems, a sensibility analysis of thermocline storage tanks is being carried out. A simulation model in Matlab developed by Ciemat is being used for it. With this study the influence of using different storage materials, materials fillers and porosities, working conditions, etc. are being analyzed.

(b) Experimental evaluation of components, equipment and procedures.

Up to now, the experience in characterization and evaluation of hydraulic components for molten salt circuits is quite reduced while the specifications given by components manufacturers do not fit well with the expected working conditions in a CSP molten salt storage system. There is not yet any standard testing procedure to characterize such components. To help in solving these problems, Ciemat is being working on two testing loops with molten salts as heat transfer fluid: one small circuit where valves, auxiliary heating trace and piping can be tested and a much bigger one where also vertical pumps and control strategies can be studied and tested. It is expected that by middle of 2011 both molten salt testing loops will be available. Several companies have already shown interest in testing components in these loops. With a total of 12 companies, Ciemat is working today's, trough the Structural Material Division, to study the compatibility of different structural materials due to corrosion with molten salts.

In 2010 Ciemat has actively collaborated with the new European initiatives like the European Research Alliance (EERA) and Knowledge and Innovation Communities (KIC). Under the KIC Innoenergy, Ciemat has launched and led in 2010 the project TESCONSOL on thermal storage development for CSP. This project was one of the four selected projects on Renewables by the European Institute of Technology (EIT).

Publications:

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[5.8] Adinberg, R.; Tamme, R.; Lange, D.; Py, X; Rojas, E.; Fabrizi, F.; Hänchen, M., Report on the Methodology to Characterize Various Types of Thermal Storage Systems, D15.1 SFERA project, Julio 2010

5.3.2 Supporting tools and test facilities

SFERA: Solar Facilities for the European Research Area

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Participants: CIEMAT (E), DLR (D), CNRS (F), PSI (CH), ETHZ (CH), WIS (IL), ENEA (I), and DIN (D), UPS Toulouse (F), AUNERGY (E), CEA (F), INESC-ID (P)
Start: July 1, 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.

Figure 5.16 SFERA project Logo

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 industry, what SFERA is and what services are offered. This will give many potential users the opportunity to become aware of the possibilities existing for making use of the SFERA infrastructures.

Test Facility for Solar-Driven Expansion Machines, Thermal Energy Storage, Absorption Chillers and Desalination Units

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Participants: Fraunhofer ISE

The key components for solar polygeneration (e.g., medium and high temperature collectors, thermal energy storage, small expansion machines and absorption chillers) are at various levels of development. There is not yet a demonstration combined solar heat, cold and power system. Many components that would be suitable for solar polygeneration have not yet been tested or optimized for the dynamic behavior of solar systems.

A test facility for solar polygeneration components was erected and commissioned at Fraunhofer ISE. It was designed to be as flexible as possible. A gas fired burner allows the dynamic behavior of a collector field to be emulated. Its thermal capacity is 250 kW at a maximum temperature of 300°C. The cycle is designed for pressures up to 30 bar and water or organic working fluids can be used. A water brake allows a wide variety of expansion machines and load profiles up to 40 kW_e and 12000 rpm to be tested. It will be used to test different expansion

Figure 5.17 Photo of test facility

machines and working media for small solar polygeneration systems. In addition, the facility may be used for testing and characterization of thermal storage systems, chillers and desalination units. The facility was successfully commissioned and is now ready for testing.

Kingdom of Saudi Arabia Digital Solar Atlas

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Christoph Schillings, christoph.schillings@dlr.de
Participants: Raed Bkayrat (KAUST), Zuhair Abussaud (Saudi ARAMCO), Christoph Schillings (DLR)
Funding: KAUST

Siting and planning of solar energy projects needs precise data about the available solar resource as solar irradiance is the "fuel" of a solar power plant. In most cases the quality of these data is insufficient. Ground measurements are expensive, and therefore, the measurement network density is usually scarce. Satellite-based solar resource assessment can assist in identifying the best sites and overall potential. Historical satellite-based information on solar radiation in combination with actual accurate ground measurements gives the most reliable information for the available solar resource for a specific site. Also regional or country-wide solar maps can be derived from satellite-based solar information.

The King Abdullah University of Science and Technology (KAUST) along with Saudi ARAMCO commissioned the German Aerospace Center (DLR) to develop a digital atlas of the Direct Normal Irradiance (DNI) for the Kingdom of Saudi Arabia (KSA). The development of a digital Solar Atlas is a first step in providing a reliable solar radiation database allowing the solar resource to be harvested in KSA.

The well established method, developed by DLR for deriving solar radiation from satellite data, is called Solar Energy Mining (SOLEMI). The meteorological quantity “solar radiation” is not measured directly (as it is by ground instruments) but is derived by parameterization of the atmosphere. The parameters which most influence solar radiation, mainly clouds, aerosols, water vapor, ozone, CO_2 and O_2 (mixed gas), and altitude, are taken into account to parameterize the atmosphere. With a broadband radiation model the solar radiation at ground level can be derived.

The most influential parameter, clouds, is taken into account by analyzing half-hourly information on the system ground-atmosphere as observed by the METEOSAT meteorological satellite. METEOSAT half-hourly data for ten years (1.1.1996-31.12.2005) were analyzed for the KSA Solar Atlas. Furthermore, atmospheric data for aerosols, water vapor, ozone and mixed gases on different time scales (daily to monthly) provided by other satellites or models were also used.

The result of this analysis is information on the Direct Normal Irradiance (DNI). Mean monthly and annual sums of DNI with a spatial resolution of up to 30 arcsec (approx. 1 km²) were chosen for mapping these data. Figure 5.18 illustrates the mean annual sum of DNI for the Kingdom Saudi Arabia.

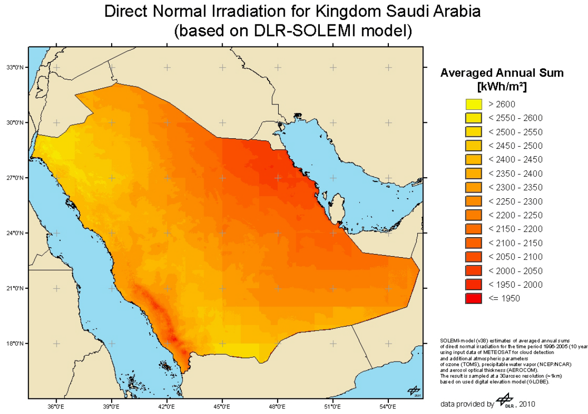

Figure 5.18 Mean annual sum of Direct Normal Irradiation [kWh/m²/year] for the analyzed time period 1996-2005 for Kingdom Saudi Arabia calculated with DLR-SOLEMI model.

Current work is validating the satellite-derived DNI for selected sites in the KSA. A first comparison with existing historical ground measurements shows a deviation of about 5% for relative Mean Bias Deviation for annual sum and 39% for relative Root Mean Square Deviation. The SOLEMI model can be adapted to match reliablem accurate ground measurements to decrease the deviation. This work is still in progress.

As the final Solar Atlas is provided in a digital format, the data can be used in Geographical Information Systems (GIS) for further spatial analysis. KAUST, along with key stakeholders in Saudi Arabia, is working on making this data readily available for interested parties.

Detailed optical characterization of solar mirrors

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Participants: Fraunhofer ISE
Funding: This work was funded by industrial partners, the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) under the “KoM-Gen” project and by a PhD scholarship of the Heinrich Böll foundation.

The optical properties of reflector materials decisively influence the efficiency of concentrating collectors for solar-thermal power stations and process heat. Therefore, in 2010, we developed a series of processes and models for detailed optical characterization of new reflector materials. We investigated, e.g., the reflectance behavior of aluminum or polymer-film reflector systems and determined the effect of beam expansion on the energy yield collectors by optical simulation (ray-tracing).

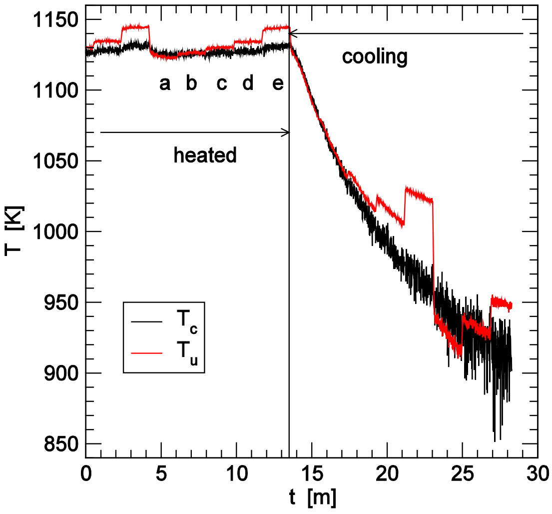

Figure 5.22 Pyrometric temperature of a Sigradur G sample in presence of external radiation. T_u: uncorrected temperature, T_c: temperature signal obtained after subtraction of external radiation. Relative intensity of external radiation is varied as 0% (a), 15% (b), 34% (c), 54% (d), and 100% (e) for one full cycle. From [5.9].

Both for the selection of the key component, the reflector, and for simulating the collector energy yield, knowledge of the optical reflectance for all relevant incidence angles is essential. This applies particularly to on aluminum or polymer film-based reflectors. They feature a particularly anisotropic scattering characteristic (Figure 5.19) and are often inadequately characterized by standard methods and models.

In our laboratory, we measure relevant optical properties such as the angle-dependent, direct-direct reflectance, beam expansion by the reflector surface and the form stability of reflectors which are mounted, e.g., in parabolic troughs. In particular, for new reflector materials of multi-layer stacks, we determine the angle-dependent, direct-direct solar reflectance for incidence angles up to 60°, as interference effects can have a strong effect here. The resulting function can then be transferred directly for use in the yield analysis of a collector system.

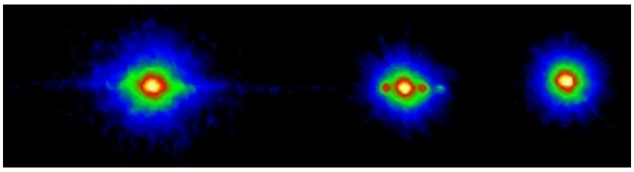

Figure 5.19 Reflectance profile of an aluminium-based reflector (left), a back-surface glass mirror (centre) and a reflector based on multi-layer polymer films (right).

We used our laser and white-light goniophotometer to acquire information on the characteristic scattering profile of a reflector, (Figure 5.20). We used them to measure the angle-resolved profile of a reflected light beam typically at intervals of 0.1 ° and extract from it the parameters for a modeling function to describe scattering by the surface. For example, we modeled aluminum-based reflectors with two Gaussian distributions and an exponential function. Rolling traces on the reflector sheet cause an anisotropic scattering distribution which must be include in the optical simulations for realistic results.

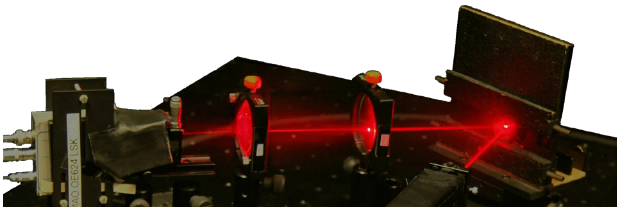

Figure 5.20 Laser goniometer for detailed characterization of the angle-resolved reflectance profile of reflector materials (laser beam superimposed on photo).

Finally, we also determined the three-dimensional curvature and form stability of a reflector by fringe reflectometry (deflectometry). In this technique, a camera records the distortion of a dynamic sinusoidal pattern as reflected by the mirror. The distortion is analyzed and from this, the local surface angle of the reflector is determined over the entire reflector area or the section recorded by the camera. In 2010 we improved our beam based camera calibration method to identify deviations in the surface angle of less than 1 mrad and to detect manufacturing faults and defects in mirrors with very short focal lengths.

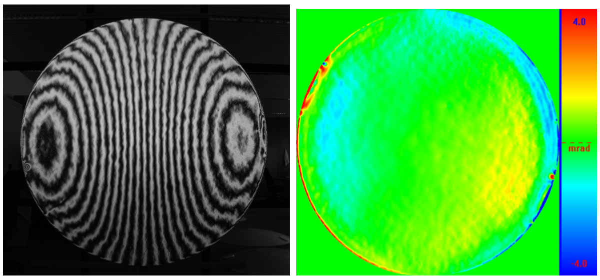

Figure 5.21 Detailed analysis of surface slope with the fringe reflection technique (right: deviation of surface slope of a parabolic dish, left: reflected fringe pattern)

Measuring Temperatures in a High Concentration Solar Simulator – Demonstration of the Principle

Participants: PSI (CH)
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Funding: EC FP7 project SFERA, Contribution to Task 12.2
Duration: July 1, 2009 – June 30, 2013

Background: Several pyrometric methods for measuring temperatures in presence of intense external radiation have been developed for use in solar furnaces. They either rely on the absence of external radiation in specific wavelength regions (e.g., solar-blind pyrometry) or use an additional strong light source and a cold reference target (e.g. flash-assisted multi-wavelength pyrometry – FAMP; pyro-reflectometry) to sample the spectrum of the external radiation.

Purpose: Develop a simple pyrometric method specifically suited for arc-lamp solar simulators.

Achievements in 2010: A new single-color pyrometric method for radiatively heated samples by an artificial light source has been developed [5.9]. The method allows separation of the external radiation reflected by a sample from its thermal emission as the intensity of arc lamps, commonly used in high concentration solar simulators, can be electrically modulated at frequencies well above the thermal response ($\omega \gg 1/\tau_{th}$) of the sample. Thus, the external radiation reflected by the sample can be measured separately using a phase sensitive detection scheme at the modulation frequency of the light source. In addition, a composite signal consisting of the thermal emission with the reflected external radiation superimposed is detected. This signal is obtained by observing the sample with a mechanical chopper operating at a different frequency placed in the observation path. The composite signal is measured simultaneously with identical optics and detector. The thermal emission of the sample can then be extracted as the difference of the two measured signals after suitable calibration.

Publications:

[5.9] Alxneit I. (2011) Measuring temperatures in a high concentration solar simulator – Demonstration of the principle, *Solar Energy* 85(3), 516-522.

Development of a space-resolved specular reflectometer

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Participants:	DLR
Funding:	DLR

The measurement of specular reflectance with spatial resolution offers several advantages in terms of aging characterization of solar reflectors, especially when they suffer from localized corrosion. For this purpose, a space-resolved specular reflectometer was developed (see Figure 5.23). With this instrument, the specular reflectance of flat mirror samples can be evaluated at any point of its surface.

The instrument prototype (see Figure 5.24) enables specular reflectance to be measured at 3.5, 7.5 and 12.5 mrad acceptance angle. Using a filter wheel, measurements can be taken at 410, 500 and 656 nm. The system has a spatial resolution of 37 pixel/mm. The measurement spot size is 5 cm in diameter. The prototype was shown to have ±0.6% precision specular reflectance at 12.5 mrad acceptance angle. The instruments precision was determined by comparing the measurements to the results of the Round-Robin-Test performed for various reflector types with commercially available instruments by NREL/DLR/CIEMAT.

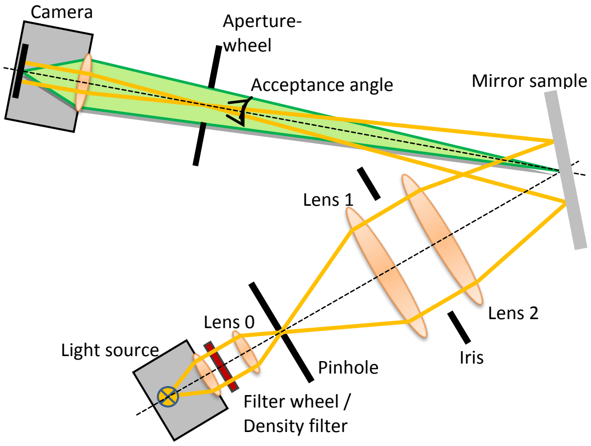


Figure 5.23 Design of the space-resolved specular reflectometer

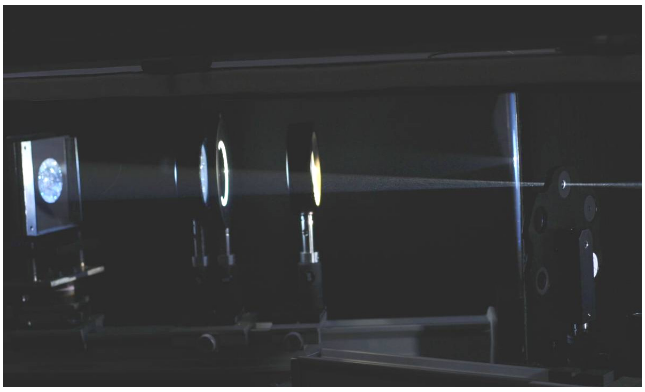


Figure 5.24 Reflected light beam in the prototype setup

The instrument is especially useful for periodically monitoring the percentage of corroded surface on reflector samples in outdoor exposure or accelerated aging tests (see Figure 5.25). Local corrosion spots can be detected and their influence on the reflectance behavior can be quantified. The corrosion rate and its influence on reflectance are important parameters in order to develop service life time models to predict the durability of solar reflectors.

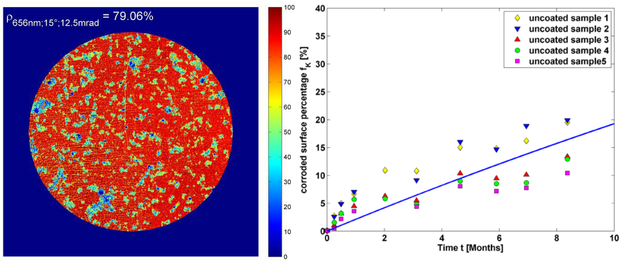


Figure 5.25 Reflectance map of a corroded reflector sample and percentage of corroded surface over outdoor exposure time

5.3.3 Advanced technologies and applications

Largest Solar Cooling System in the Middle East for a Showcase Football Stadium in Qatar

Contact: Christian Zahler, Tobias Schwind, Andreas Häberle, info@mirroxx.com
Participants: Mirroxx GmbH, PSE AG

Qatar has successfully applied for the hosting of the 2022 FIFA World Cup with a showcase football stadium designed by ARUP associates. Key point of the sustainable energy concept is a solar cooling system powered by a concentrating solar collector field with 1.408 m² aperture area rated at a thermal peak power of 700 kW manufactured and installed by the German company Mirroxx.

The Mirroxx Fresnel collector field consists of four strings made of 16 modules each and has a total primary mirror area of 1408 m². It heats water at 16 bar pressure to temperatures of up to 200°C.

A pressurized hot water storage with a volume of 40 m³ allows for dispatched operation of the absorption chiller to avoid operation during noon hours with high ambient temperatures thus reducing the water consumption of the cooling tower. The double-effect lithium bromide absorption chiller manufactured by the Indian company Thermax has a nominal cooling capacity of 650 kW. The cold is stored in eutectic tanks beneath the stadium and distributed in the building by air-handling units manufactured by Desiccant Dry Air.

The linear Fresnel collector design of Mirroxx bears many valuable features: high ground usage factor, easy access for cleaning, large absorber tube diameter resulting in low pressure drops, thus decreasing electricity consumption and investment costs for the pumps, low heat losses due to high-quality vacuum absorber tube.

With less than 5 months lead time for commissioning under the harsh weather conditions of summer time in Qatar, Mirroxx demonstrated its capability of handling large and time-critical projects in any place of the world. Apart from solar cooling projects Mirroxx is about to deploy its technology for direct steam generation in industrial process heat applications.

Publications:

[5.10] Zahler, C., Berger, M., Häberle, A., Louw, J., Schwind, T., *Mirroxx Fresnel Process Heat Collectors for Industrial Applications and solar cooling*, 2009, 15th International SolarPACES Symposium on Solar Thermal Concentrating Technologies, Berlin, Germany

Durability of reflector materials

Contact: Aránzazu Fernández García, arantxa.fernandez@psa.es;
Participants: CIEMAT and DLR;

In order to reduce electricity generation costs of concentrating solar systems, a number of low-cost reflector materials are currently being developed by mirror manufacturers. The new materials need to withstand the rough outdoor conditions without a significant loss in specular reflectance.

The purpose of this project is to characterize and analyze the durability of the reflector materials used in solar concentrating systems. One of the most challenging goals is to develop accelerated aging test methodologies that are suited to reproduce realistic outdoor degradation in a short period of time. The actually used durability tests for solar reflectors have been adopted from other industries and are thus not always adequate. So far there are no testing procedures that allow reliable service life time predictions for solar reflectors.

The new accelerated aging lab allows the performance of several durability tests and standards. It counts with the following equipment:

Figure 5.26 Mirroxx Fresnel collector field and Showcase Football Stadium in Doha / Qatar

- Weathering chamber to control temperature, relative humidity, solar radiation and rainfall (Atlas SC340)
- Salt-spray chamber to perform corrosion tests according to ISO9227
- Ultraviolet chamber which within one hour applies an equivalent UV-dose of 14 hours of outdoor exposure in Almeria
- furnaces to control temperature or thermal cycling
- Acid rain chamber to simulate industrial environments according to DIN50018
- Taber Linar Abrasor to perform abrasion tests according to ISO9211-4
- Sand storm chamber to simulate abrasion in desert regions. It operates at wind velocities up to 30m/s and dust concentrations up to 2.5g/m^3 (See Figure 5.27).

Additionally, the lab is equipped with a machine performing continuous scrub-testing on reflector surfaces. It is used to evaluate the degradation due to the cleaning. The results will help to develop suited cleaning procedures for new reflector materials.

The laboratory allows a complete optical characterization of the reflector materials. There are several portable specular reflectometers, a 3D microscope and a spectrophotometer with an integrating sphere (See Figure 5.28) available to analyze degradation processes.

In 2010 several projects in collaboration with mirror manufacturers have been started. The projects involve accelerated aging testing and outdoor exposure testing at the PSA. Also, the performance of newly developed anti-soling coatings is evaluated by periodical measurements of outdoor exposed samples.

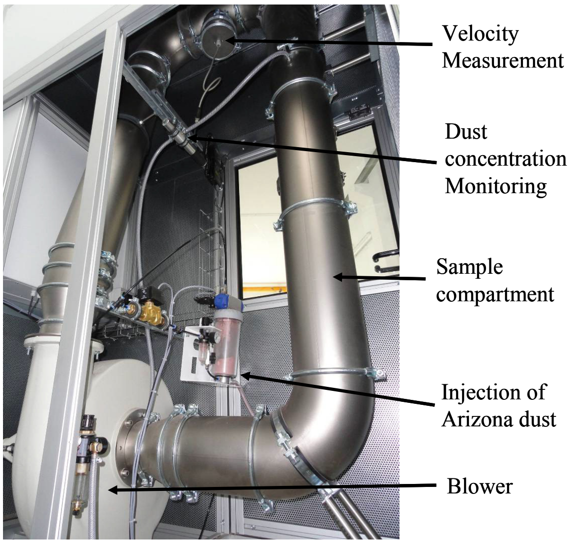


Figure 5.27 Sand storm chamber

Figure 5.28 Perkin Elmer Lambda 1050 Spectrophotometer in the solar reflector test laboratory

5.3.4 Standards for CSP components

Development of guidelines for standards for CSP components

Contact: Peter Heller, peter.heller@dlr.de
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 set up:

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

In 2010 a SolarPACES workshop with more than 40 participants was held in Perpignan in conjunction with the SolarPaces Symposium. The intensive discussion between industry members and research institutions showed close agreement in the developed methods. From 2010 on, this activity has also been funded by a 3-year SolarPACES Project.

In Group a) a round robin test was initiated to pre-define guidelines for reflectance measurements. A core team will prepare a proposal for the most promising procedure. The goal is to publish a first draft SolarPACES Guideline document in spring 2011.

Group b) showed significant advances and intends to complete the guideline on mirror/module shape measurements by spring 2012.

Another workshop was announced for spring 2011 in Granada, Spain, to report on the progress of the four working groups and to discuss proposals for inputs of Task III to the SolarPACES strategic plan for 2011-2015.

Solar Weighted Reflectance Measurement Guidelines for Solar Mirrors

Contact: Stephanie Meyen, stephanie.meyen@dlr.

Within the Task III activities, the 2-year project “Development of guidelines for standards for concentrating solar power (CSP) components” one mayor goal was to create a guideline document for the measurement of solar weighted specular and hemispherical reflectance of solar mirror material samples with commercially available instruments. A group of experts from DLR, CIEMAT and NREL worked together on this task under the leadership of DLR.

The basic procedures for hemispherical measurement with a spectrophotometer equipped with an integrating sphere and for specular reflectance measurement with a portable specular reflectometer were agreed on. The relevant parameters, which should always be indicated with wavelength λ, incidence angle θ and acceptance angle φ (see Figure 5.29), were defined as follows:

Specular reflectance = $\rho_s(\lambda,\theta,\varphi)$

Solar weighted specular reflectance = $\rho_s(SW,\theta,\varphi)$

Hemispherical reflectance = $\rho_h(\lambda,\theta,h)$

Solar weighted hemispherical reflectance = $\rho_h(SW,\theta,h)$

Then a round robin test was performed between these three organizations with material samples that represented all types of solar mirror materials that are currently on the market. These were 2nd surface of 4 mm, 3 mm, 1.6 mm and 0.95 mm thick silvered glass mirrors, 1st surface silver polymer film and 1st surface enhanced aluminum mirrors. The results of the round robin test were presented in the 2010 SolarPACES conference paper, “Standardization for Solar Mirror Reflectance Measurements – Round Robin Test”.

The main results of the work revealed a measurement uncertainty with standard deviations of $\sigma_s = 0.004$ for specular reflectance measurements and $\sigma_h = 0.007$ for hemispherical reflectance although within one laboratory much better repeatability could be achieved. Better accuracy had been expected especially for hemispherical reflectance measurements with a spectrophotometer.

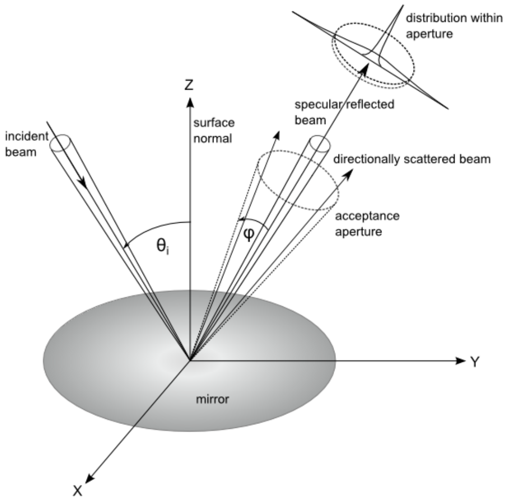


Figure 5.29 Schematic of reflectance parameters.

The round robin test results helped to identify the main reasons for measurement uncertainties, which revealed that the use of the correct reference mirror and its calibration status plays a major role, as well as the size of the integrating sphere, operator experience, small variations in measurement method and sample homogeneity. It was pointed out that improvements of available instruments are necessary to improve measurement accuracy and the requirements that these should fulfill were also identified. On the basis of this work, the goal of writing a first version guideline document was achieved at the end of the year, and it can now be downloaded at the SolarPACES website as “Measurement of Solar Weighted Reflectance of Mirror Materials for Concentrating Solar Power Technology with Commercial Available Instrumentation”.

6 Task V:
Solar Resource Knowledge Management

Task Representative: Richard Meyer, Suntrace GmbH
Task Participants:

- Austria: BlueSkyWetteranalysen, ASIC
- Canada: Environment Canada, CANMET
- European Union / Italy: Joint Research Center (JRC)
- France: EdM/Armines, LASH-ENTPE
- Germany: DLR, Suntrace GmbH, Univ. of Applied Sciences Magdeburg-Stendal (H2M), Univ. of Applied Sciences Ulm, Univ. of Oldenburg (EHF)
- Slovakia: GeoModel s.r.o.
- Spain: CIEMAT, CENER, Univ. of Jaén, Univ. of Navarro
- Switzerland: Meteotest, Univ. of Genève (UNIGE)
- USA: NREL (Operating Agent), NASA, SUNY

6.1 Nature of Work and Objectives

"Solar Resource Knowledge Management" is an IEA Task under the Solar Heating and Cooling (SHC) Programme Implementing Agreement with Dr. David Renné from NREL as Operating Agent. 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 scope of work addresses all solar resource topics. It covers satellite-derived solar resource products, ground-based solar measurements as well as solar forecasting and data dissemination methodologies. The Task equally supports solar thermal heating and cooling, photovoltaics and concentrating solar applications. However, for best serving the objectives of SolarPACES this report focuses on direct solar radiation, which can be concentrated.

The three main goals in this Task are:

- Standardization and benchmarking of solar radiation data sets for better comparability and acceptance of data products.
- Improved data availability and accessibility in formats that address user needs.
- Development of methods that improve the quality and the spatiotemporal coverage of solar resource products, including forecasts.

6.2 Scope of the Task

The collaborative IEA Task SHC Task 36 / SolarPACES Task V on solar resources is structured in the following three Subtasks:

Subtask A:	Standard Qualification for Solar Resource Products (Lead by Prof. Dr. Hans Georg Beyer, Hochschule Magdeburg-Stendal (H2 Magdeburg), Germany now at Universitetet Agder, Grimstad, Norway)
Subtask B:	Common Structure for Archiving and Accessing Data Products (Lead by Prof. Lucien Wald, EdM/Armines, France)
Subtask C:	Improved Techniques for Solar Resource Characterization and Forecasting (Lead by Dr. Detlev Heinemann, Oldenburg University, Germany)

This IEA Task focuses on the development, validation, and access to solar resource information derived from data collected by satellite-based platforms, surface-based measurement stations and numerical weather models. Subtask A defines standards for comparison of irradiance products with respect to energy applications. Various quality control procedures for solar irradiance time series are reviewed and improved. Benchmarking of solar resource products against reference measurements will help the user to identify uncertainties better and select products, which are sufficiently reliable.

Subtask B examines the means by which the data can be made available to users mainly through various web-based hosting schemes and distributed networks. Activities under this task mainly include definition of data exchange protocols, development of a prototype web-based system, implementation of a network of solar providers, and preparations for automatic access for commercial applications.

The objective of Subtask C is to conduct essential R&D to improve the accuracy and the spatial and temporal coverage of current techniques, including the introduction of solar resource forecasting products. Key activities to meet this objective are to improve satellite retrieval methods for solar radiation products; past and future climate variability of the solar resource will be studied to estimate the uncertainty of solar yields. Furthermore, options for forecasting solar radiation in time scales from hours to several days will be developed.

After a brief general presentation, the structure of this report follows the sequence of the Subtasks as explained above. Results described are mainly those achieved in 2010. The report also refers back to earlier work for better comprehension.

6.3 *Activities During 2010*

A Task Experts Meeting was held at IEA Headquarters in Paris, France on 8-11 March, which consisted of two parts: 1) a review of progress to date, and 2) a Task Definition Workshop to outline a new Task Annex. Another Task Experts Meeting was held in conjunction with the Eurosun 2010 Conference in Graz, Austria. The meeting focused on development of a Draft Annex for a new task entitled "Solar Resource Assessment and Forecasting". The Annex was presented to the IEA/SHC 68th ExCo meeting in Cape Town, South Africa in November 2010 and approved as new Task 46. In 2011 the plan of work should be defined and it is planned to receive approval for continuation of the Task in collaboration with SolarPACES and PVPS.

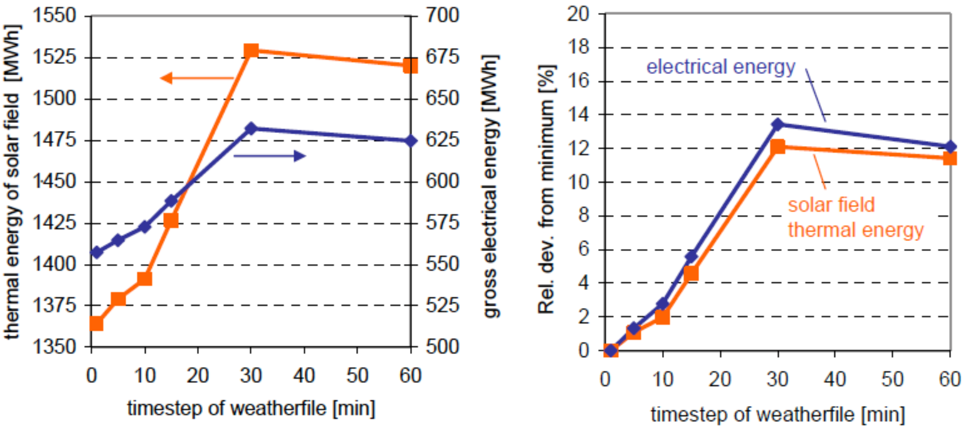


Figure 6.1 Effect of time-resolution of the meteorological input data on yields of a solar thermal power plant on a day with broken clouds (Hirsch et al., 2010).

A number of Task-related papers were presented by task participants at Solar 2010 in Phoenix, Arizona, the 25th European PV Solar Energy Conference, the SolarPACES Conference in Perpignan, France, and the Eurosun 2010 Conference in Graz, Austria.

6.3.1 Standard Qualification of Solar Resource Products

Subtask A defines procedures for benchmarking and applies them to the available solar radiation datasets. A key activity in benchmarking exercises is setting up qualified reference datasets, which are based on high-quality ground-based radiation measurements. Benchmarking is an essential prerequisite for standardizing solar radiation products and their further application.

Quality measures for solar resource products have been introduced under the European MESoR-project (Hoyer-Klick, et al., 2009). The quality indicators are separated in "first order" and "second order" statistical parameters, which shall be used to characterize the quality of solar resource products.

The "first order" measures involve the commonly used root mean square deviation *RMSD* and the mean bias *MB*. These are typically expressed in absolute values with units of W/m^2. For easier understanding, these values are often relative. *rRMSD* or *rMB* shall represent *RMSD* or *MB,* respectively, as percentages, typically related to the reference irradiance for the site. Because there is no clear definition, which reference should be taken in the numerator (e.g. actual value, average over 24 h or related only to duration between sunrise and sunset), it is recommended that deviations of solar irradiance be expressed as absolute values. This also has the advantage that *RMSD* and *MB* are more directly connected to the effect on the solar energy system power output.

Furthermore, it is clear that the *RMSD* strongly depends on the time-resolution of the time-series analyzed. Up to now, analysis and simulation of solar energy systems has been done in 60-min time steps. Newer satellites and models now offer the option of deriving 15-min time steps, and could be further roughened by statistical post-processing, e.g., down to 1 min. More and more people in the CSP industry realize that for realistic results performance simulation models must be run in much higher time resolution. Hirsch et al. (2010) developed a dynamic model, which is capable of simulating the most important transient effects of a parabolic trough plant like it is typically being built in Spain today. By entering meteorological of various time-resolutions as input data in this dynamic model, it was found that when applying only 60 min data, the calculated production of a CSP plant can be overestimated significantly, especially on days with intermittent clouds (Figure 6.1).

The clear implication for benchmarking of solar resource products is that data need to be analyzed in various time resolutions. This is one of the objectives of the new project entitled "Standardizing and Benchmarking of Satellite-Derived DNI-Products". This ongoing DNI-benchmarking project, which is partly funded by SolarPACES, started in 2010.

A recommendation arising from this is to always indicate the time-resolution, which a quality refers to, e.g. $RSMD_{15min}$ for *RMSD*-values referring to a 15 min time resolution. To be even more precise, the spatial resolution of a dataset to be characterized must also be specified. It is known that some providers deliver solar radiation data products in various spatial resolutions. Depending on the sampling rate, spatial averaging sometimes has favorable effects on the *RMSD,* as neighboring satellite-pixels help to smooth out the shortcoming of having only 1 or a maximum of 4 observations per hour

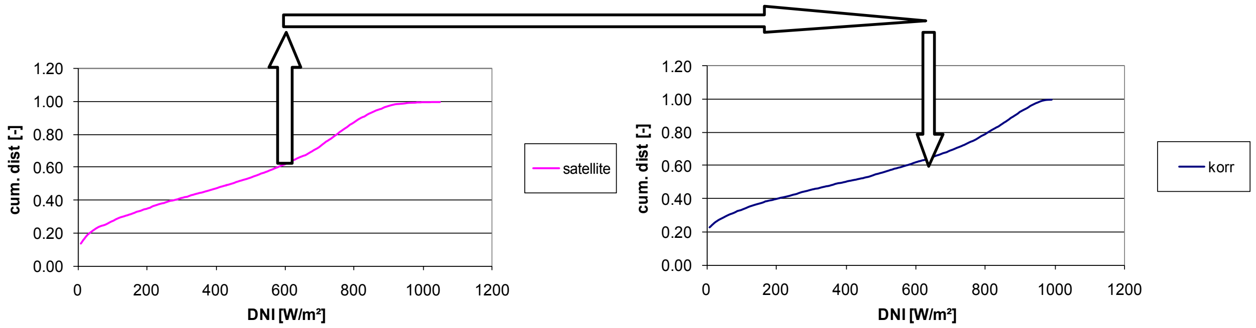


Figure 6.2 Correcting satellite-derived DNI data distributions with ground-based measurements (Beyer et al., 2010).

to derive a 60 min value. Because DNI spatial and temporal variability is much stronger than GHI, it is proposed that DNI products be benchmarked not just in various time-resolutions, but also in various spatial resolutions, if provided by the data suppliers. It is proposed that the RMSD should also indicate the nominal spatial resolution, e.g. $RSMD_{15min,1km}$ or $RMSD_{60min,5km}$.

On the contrary, the bias *MB* of a dataset should be independent of the time resolution and thus does not need this specification. As the *RSMD* represents a combination of the bias and the standard deviation *SD* of the two time series considered, it would be better to use the two independent values, *MB* and *SD,* rather than the pair of *MB* and *RMSD*. The bias *MB* is used to express the systematic deviation of two data and *SD* the more random differences, which often average out.

"Second order statistics" involve measures like the Kolmogorov-Smirnoff Integral (KSI) or the measure "OVER", which has the additional condition of integrating only differences above a certain threshold (Espinar, et al., 2008). The KSI and OVER were invented in order to have a single number representing how well a frequency distribution of solar irradiance agrees with a reference frequency distribution at a site, e.g., a satellite-derived DNI-time series with the ground-measured DNI time series at the same site.

However, it is recognized that the KSI also depends on the number of data samples available. Ongoing work indicates that there is a poor correlation of the KSI with deviations in annual electricity production of CSP plants. Thus, KSI and OVER do not seem to be good measures for expressing the congruence of frequency distributions with a reference. Thus, another quality parameter should be found which better correlates the characteristics of DNI time series with CSP-plant production.

Another activity in Subtask A deals with post-processing of satellite-derived solar irradiance data. If overlapping ground-based solar radiation measurements are available at the site, the satellite or model-derived data can be adjusted to the ground-based data. Up to now, this has been done primarily with monthly or annual data sets by adjusting the observed biases between the satellite and ground station.

An extended approach developed under Subtask A is to modify the distributions of satellite data sets according to site-specific distribution of measured data following an algorithm of Beyer et al. (2010). This is done by mapping the original values to the target values according to the value of the cumulative distribution, as depicted in Figure 6.2, which results in a modified more realistic distribution curve.

Environment Canada and Natural Resources Canada have collaborated on development of a CCD optical fiber spectrometer system for the near instantaneous measurement of spectral global, direct, diffuse, reflected and southward-tilted irradiances from 0.3 µm to 1.0 µm. A recent report (Morley et. al, 2010) includes a description of system components and an assessment of the spectrometer's measurement accuracy.

6.3.2 Common Structure for Archiving and Accessing of Data Products

The main goal of Subtask B is to set up a user-oriented data portal for accessing solar resource data. Unified access to such a portal was developed in the course of the EU project "Management and Exploitation of Solar Resource Knowledge" (MESoR, Hoyer-Klick et al., 2009). A prototype has been set up, and can be accessed at http://project.mesor.net. An example of the Web interface for accessing solar resource data for a location in Europe is shown in Figure 6.3. Using a Google Earth interface, users can click on a specific location of interest and a file containing the various data sources available for that location appears.

GeoModel Solar has developed and implemented new methods for its interactive map-based portal SolarGIS.

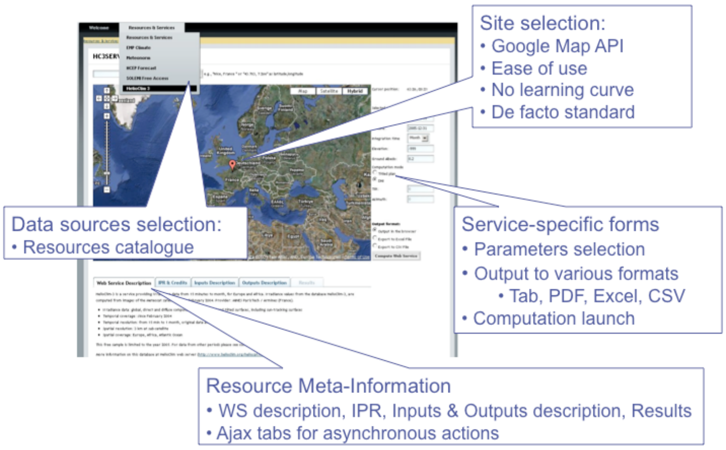


Figure 6.3 Prototype web interface for accessing solar resource data for a location in Europe (Source: Armines).

The portal links to a large database of global horizontal (total) and direct normal irradiance, air temperature, the digital elevation model SRTM-3, and to other geographic data, such as population density and land cover. Access is through the user-friendly web-GIS application http://solargis.info/imaps/ (see Figure 6.4). The database now covered is similar to DLR-Solemi (http://solemi.de/) and IrSOLaV (http://www.irsolav.com/) using the Meteosat Prime and Meteosat East satellites.

Meteosat Prime (MP) refers to all satellites orbiting at or near the Prime meridian (0° longitude), for which the European Meteosat satellites have been delivering almost uninterrupted 30 min time resolution observation from 1983 to mid 2006.

Since early 2004 Eumetsat in addition to its Meteosat First Generation (MFG) satellites started operational services of the Meteosat Second Generation (MSG) in the Meteosat Prime position. MSG has the advantage of a halved repetition period of 15 min.

Compared to MFG with a nominal resolution of 2.5 km in the 'visible' panchromatic channel (VIS) the VIS-channel of MSG now has an enhanced nominal spatial resolution of 1 km at the sub-satellite point near 0°, 0° for the MP-mission. However, due to a smoothing wider point-spread function, the actual resolution is only around 1.3 km by 1.3 km at the equator. Due to a less favorable viewing geometry, the spatial resolution then increases continuously with distance from the equator and also with distance from the meridian, at which the geostationary satellite is operating.

In 1998 the MFG-satellite Meteosat-5 was drifted to a new geostationary position at 63°E to widen the view towards Asia and the Indian Ocean. Since mid-1998, operational data have been recorded and archived for this Meteosat East ME-position. In late 2006, Meteosat-5 was relieved by Meteosat-7, which has since been operational at 57°E longitude. Unfortunately for the Far East and Western Australia, a position where the sub-satellite point is around 650 km more in the West.

With their extensive satellite databases the services of IrSOLaV, SolarGIS, and Solemi, now can provide solar resource products for Europe, Africa, most parts of Asia, and the Eastern part of South America and the West coast of Australia.

The other activities in this Subtask have been completed. Liaison with the Global Earth Observation System of Systems continues, with a focus on adapting best practice methodologies for web portal design. This work will be continued in the Task continuation starting in 2011.

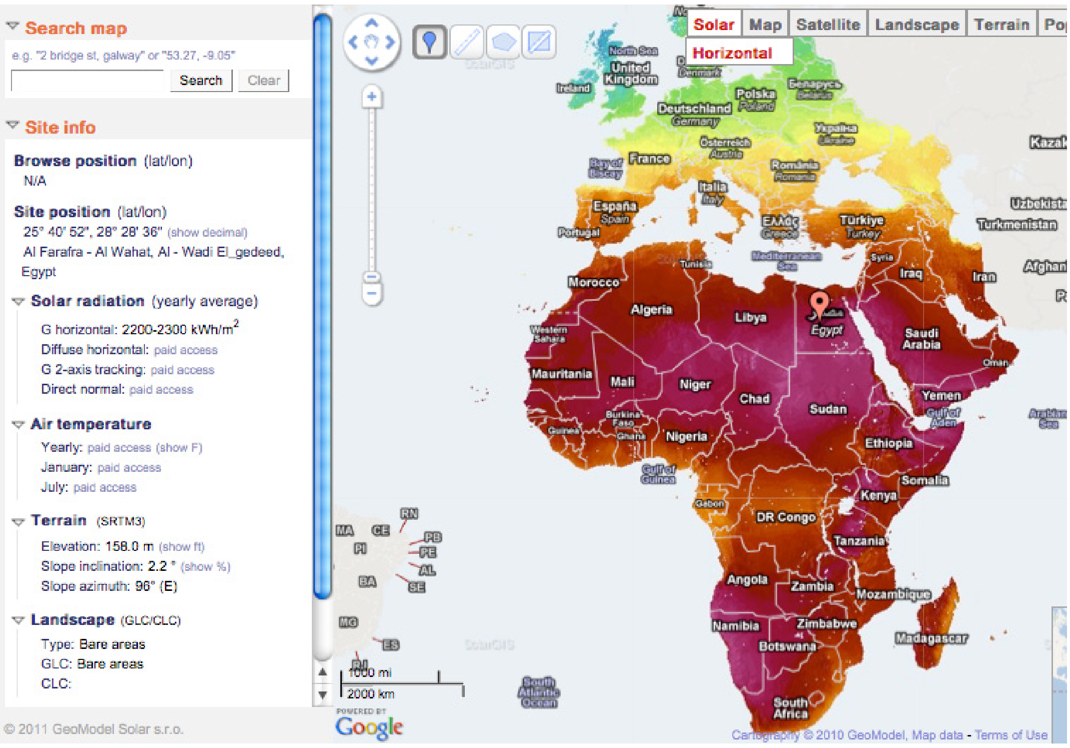
6.3.3 Improved Techniques for Solar Resource Characterization and Forecasting

The purpose of Subtask C is to improve existing solar resource products and generate new ones. Spatial and temporal coverage of current satellite-based solar resource products are being improved, leading to higher absolute and relative accuracy. Long-term variability of solar resources in connection with climate change are being monitored and assessed. Techniques for forecasting solar radiation are a new key activity in this Subtask.

Activity C1 aims at improving satellite solar radiation product retrievals. Several Task Participants report work in 2010 on this subject:

In 2010, a new set of algorithms (Šúri and Cebecauer, 2010) was developed and implemented in SolarGIS for on-line calculation of solar radiation for any tilted or sun-tracking system. The method uses a new concept of statistically aggregated time-series of solar radiation and air temperature. The resulting meteorological time-series are advantageous, especially for more accurate simulation for PV and CSP systems.

Model development by GeoModel (Cebecauer and Šúri, 2010) is underway in collaboration with R. Perez from SUNY. This



Search map

e.g. "2 bridge st, galway" or "53.27, -9.05"

Search Clear

Site info

Browse position (lat/lon)
N/A

Site position (lat/lon)
25° 40' 52", 28° 28' 36" (show decimal)
Al Farafra - Al Wahat, Al - Wadi El_gedeed, Egypt

Solar radiation (yearly average)
G horizontal: 2200-2300 kWh/m^2
Diffuse horizontal: paid access
G 2-axis tracking: paid access
Direct normal: paid access

Air temperature
Yearly: paid access (show F)
January: paid access
July: paid access

Terrain (SRTM3)
Elevation: 158.0 m (show ft)
Slope inclination: 2.2 ° (show %)
Slope azimuth: 96° (E)

Landscape (GLC/CLC)
Type: Bare areas
GLC: Bare areas
CLC:

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Figure 6.4 Web interface for accessing solar resource data for a location in Egypt (Source: GeoModel s.r.o.).

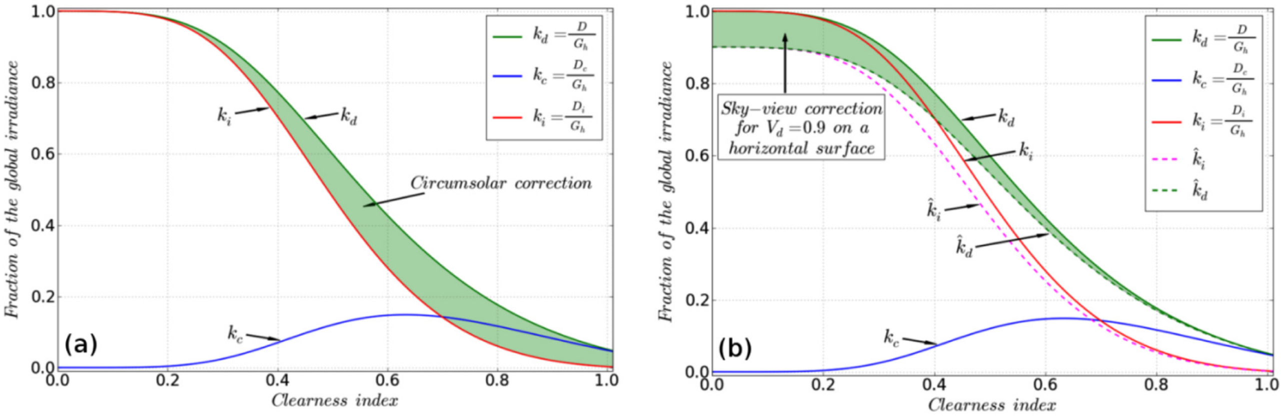

Figure 6.5 *Left: Relative importance of the correction of the circumsolar diffuse component shaded by a horizon as a function of the clearness index. Right: Relative importance of the sky view factor correction on the isotropic diffuse irradiance as a function of the clearness index (Ruiz-Arias, et al., 2010).*

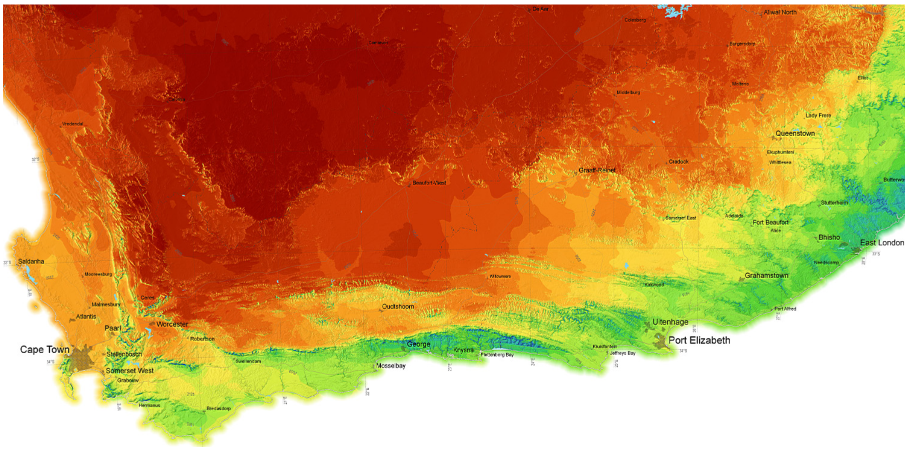

Figure 6.6 *Subset of the database calculated by the SolarGIS approach (South Africa): annual sum of Direct Normal Irradiation (Cebecauer et al., 2010).*

model is based on the framework of the SUNY/NSRDB model and includes a number of new features designed to enhance calculation accuracy, including:

- Use of Meteosat Second Generation (MSG) spectral channels both to detect snow and palliate the weaknesses of the visible-channel-based model under high-albedo resulting from specific local surface properties (e.g., salt lakes). The snow cover detection methodology is an adaptation of the method proposed by Durr and Zelenka (2008).
- Implementation of the simplified Solis model (Ineichen, 2008).
- Better representation of daily variability of solar radiation (especially DNI) due to integration of GEMS/MACC aerosol data.
- Enhancing the dynamic range to capture both ground albedo and cloud top variations over time of year, time of day and space;
- Downscaling solar irradiance with high-resolution terrain information (Ruiz-Arias et al. 2010).

This approach was adapted to the Meteosat First Generation family of satellites and implemented in the SolarGIS framework for operational calculations to Meteosat Prime and East regions. Figure 6.6 provides an example for Southern Africa. The methods has now also been implemented in operational calculation of solar irradiance for Meteosat MSG satellite (Cebecauer et al. 2010).

A contribution from the University of Jaén (Ruiz-Arias et al., 2010) and GeoModel (Cebecauer and Suri, 2010) validates the usefulness of a digital elevation model dataset (DEM) to reduce the bias present in the satellite-retrievals-based irradiance maps by the unaccounted terrain shading at high solar zenith angles (see Figure 6.5.). Inclusion of the topographic information from the DEM enhances the spatial resolution of the irradiance maps from few kilometers, for which the clouds can be derived from MSG down to 3 arc minutes (~90 m). The mean bias then is reduced for the region from 2.3 % to 0.4 %. The correction, indeed, is highly dependent on the DEM reliability. Some other aspects of the spatial variability of the irradiance have been also discussed within this work.

The GEMS AOD data set, a new atmospheric dataset – a product of the re-analysis computed by ECMWF, is incorporated into the computing chain of the new SolarGIS satellite-based model. It reduces uncertainty of instantaneous GHI and especially DNI estimates by better capturing the variability of solar irradiance. Main accuracy improvements were achieved in reduction of Root Mean Square Deviation (RMSD) and improved distribution functions. Validation is done by 9 Spanish sites, Sede Boqer in Israel and Tamanrasset in Algeria. The new satellite model using GEMS atmospheric dataset as input reduces the overall mean bias of DNI to -3.1 W/m^2 (-0.9 %). The standard deviation over the biases is 6.4 % and $RMSD_{60min}$ for hourly values is on average 123 W/m^2

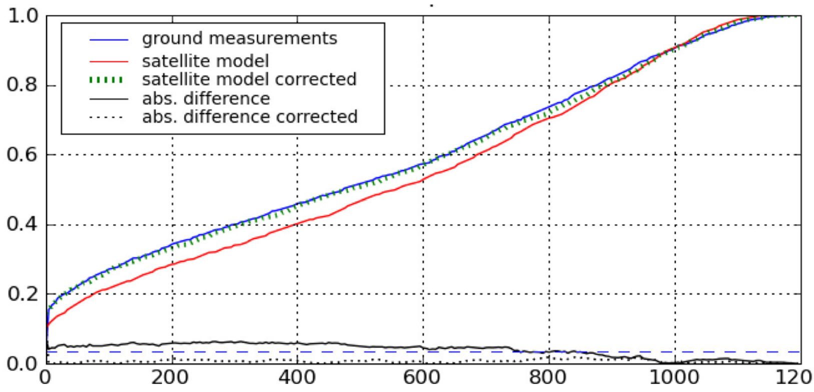

Figure 6.9 Correction of DNI (W/m^2) cumulative distribution of DNI values for Cordoba

or 36 %. Examples of these analyses are shown in Figures 6.7 and 6.8.

A common problem of satellite derived DNI databases is disagreement of frequency distribution functions (compared to ground measurements ones), which limits the potential to record the occurrence of extreme situations (e.g. very low atmospheric turbidity resulting in high DNI). Another method enhancing accuracy of SolarGIS satellite database using the ground measurements is developed by Cebecauer et al. (2010). The enhancement of the DNI accuracy is usually done for the satellite data covering a longer period of data (e.g. several years) using high-quality ground measurements which cover shorter period of time, usually several months to one year. This type of enhancement assumes that the systematic error/deviation exists in the satellite data and the magnitude of this deviation is invariant over the time. Two types of correction were made in the example of five ground stations shown in Figure 6.9 above.

For prefeasibility studies, DNI long-term monthly and annual averages are calculated using correction of bias; for feasibility studies and due diligence, enhanced hourly and 15-minute time series are produced with corrected cumulative probability distribution function.

An improvement was achieved in overall bias and/or cumulative frequency functions for all selected sites, especially for sites with wide deviation. The enhancement is effective for mitigating systematic problems in satellite-derived data such as under/over-estimation of local aerosol loads.

Aerosol climatologies with a coarse temporal and spatial resolution are currently used in solar surface irradiance schemes based on satellite imagery. DLR has assessed numerical modeling of aerosols as used in the aerosol science community and demonstrated the influence of different aerosol data sets on direct normal irradiances. A 25-year reanalysis dataset based on a chemical transport model was used to compare daily numerical modeling versus state-of-the-art use of mean monthly aerosol climatologies. Modeled aerosol optical

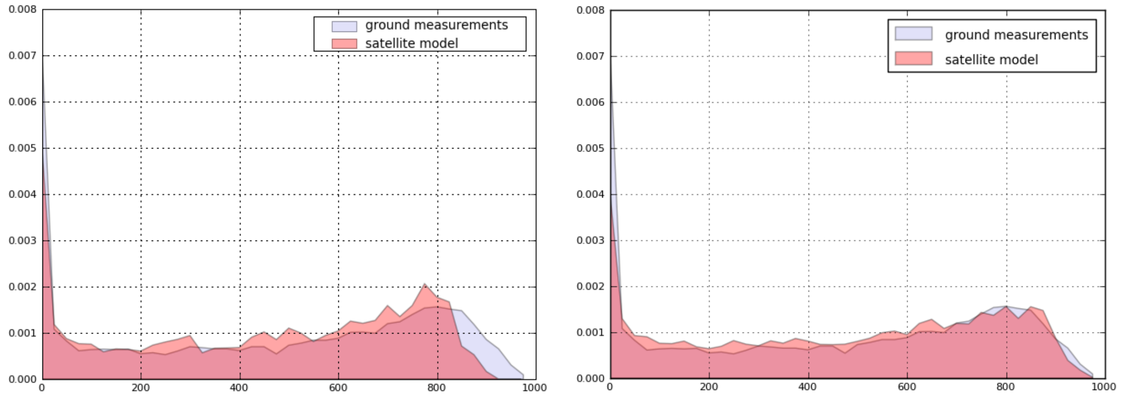

Figure 6.7 Frequency distribution of DNI values [W/m^2] for Valladolid (Spain). Left: results based on the AOD and water vapor long- Term monthly averages. Right: results based on daily values from the GEMS database

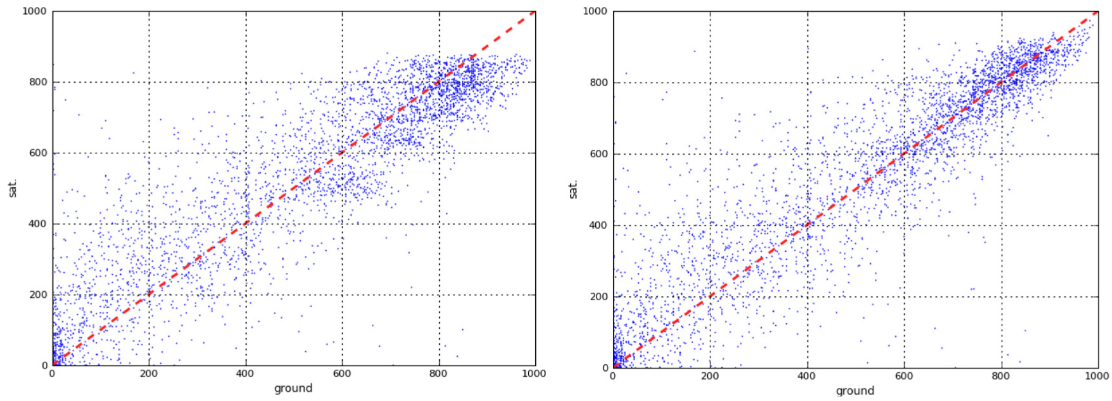

Figure 6.8 DNI from satellite model compared to ground measurements (Badajos, Spain). Left: model using AOD and water vapor long-term monthly averages. Right: model using daily values from the GEMS database (Cebecauer and Suri 2010).

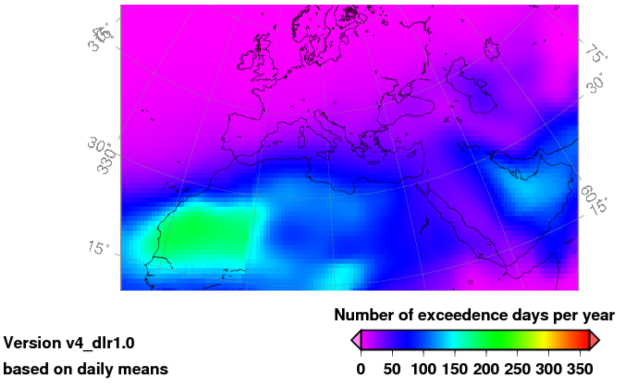

Figure 6.10 Number of days with a global irradiance extinction above 10% based on a 1983 -2007 DLR/MATCH reanalysis for the EUMENA region

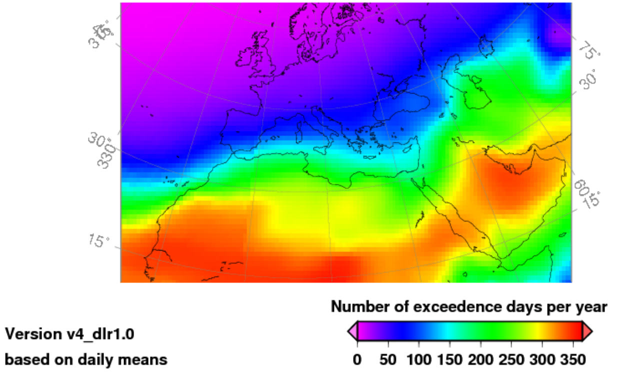

Figure 6.11 Number of days with a direct irradiance extinction above 10% based on a 1983 -2007 DLR/MATCH reanalysis for the EUMENA region..

depth was also validated against ground measurements and the potential of improved direct normal irradiance modeling was shown. A global climatology of mineral dust aerosol load and the number of occurrence of dust events with irradiance extinction of more than 5, 10, 20, and 30 % was created. Fig. 6.10 shows the number of days with global irradiance extinction above 10%, while Fig. 6.11 shows the number of days with direct irradiance extinction above 10% as a multi-annual average map for Europe, North Africa and the Middle East (EUMENA). Maximums can be observed close to the dust source regions in the Sahara and the Middle East, while other regions, such as Southern Spain, are affected by dust transport for up to 80 days per year with direct irradiance extinction above 10% caused by dust (Schroedter-Homscheidt et al., 2010).

Activity C2: Conduct Climatological Analysis of Solar Resources

Besides the information reported last year by NASA/LaRC on long-term trends based on satellite-derived solar resource data, Meteotest (Switzerland) has been examining long-term trends based on data archived in the Global Energy Balance Archive (GEBA). The study of Remund and Müller (2010) confirms observations of a global dimming, which means decrease of solar irradiance worldwide, since approximately 1960 until around 1990. Since that worldwide on average some brightening has been observed. E.g., a positive trend since 1985 is visible in Europe until last year and is in the range of 0.4 W/m^2/yr. However there are signs of a decline or even a reverse of the trend after 2005.

The use of the 20-year mean for GHI in 1981 – 2000 leads in Germany to an underestimation 2 % to 3 % lower means compared to the time period 1986 – 2005. However this is in the range of the measurement uncertainty and thus must be classified as insignificant. In most other regions the trends are even smaller or – like in China – reversed.

The changes in global radiation modeled for this century are relatively small and are mostly in the range of a few percent. In contrast to temperature, no significant changes in GHI are detected. Some climate models predict that on a global average the solar irradiation on the ground could diminish slightly, due to higher cloud frequency and enhanced optical thickness. In the Mediterranean region however the trend could be positive.

Activity C3 is developing and evaluating solar radiation forecasting procedures. For CSP industry this is highly important as solar thermal power plants can be actively controlled in a way to maximize power output or to produce more power during times, when demand and prizes are higher.

A major emphasis in Subtask C during 2010 was the test ing and benchmarking of various solar irradiance forecasting approaches

A joint effort of European partners benchmarking eight different forecasting algorithms for several regions in Europe for July 2007 to 30 June 2008 has been finalized. Results have been presented at the 24th European Photovoltaic Solar Energy Conference and Exhibition in Hamburg. Figure 6.12 gives an overview of the locations of the ground measurement stations used for benchmarking, and Table 6.1 shows the forecasting approaches of the task members with the NWP models used.

Absolute root mean square deviations (RMSD) for the different approaches are given in Figure 6.13 for the countries participating (Germany, Switzerland, Austria, and Spain). The evaluation revealed strong dependence of forecast accuracy on climate conditions. For central European stations, the relative $RMSD_{60min}$ ranges from 40% to 60%, for the Southern Spanish stations relative $RMSD_{60min}$ are in the range of 20% to 35%. At the current

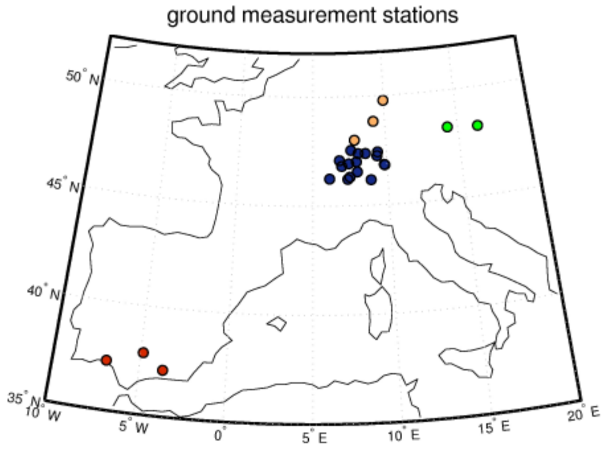

Figure 6.12 Locations of ground measurement stations for forecast benchmarking. Red: Spanish stations, orange: German stations, blue: Swiss stations, green: Austrian stations.

Table 6.1 Overview of European partners forecasting approaches

Team	Approach	NWP model with spatial and temporal resolution
University of Oldenburg, German	Statistical post-processing in combination with a clear sky model	ECMWF - 0.25°x 0.25° - 3 hours
Blue Sky, Austria,	a)"human" cloud cover forecast (by meteorologists) b) BLUE FORECAST: statistic forecast tool	for b) GFS - 1° x 1° and 0,5°x 0.5° - 3 hours and 6 hours
Meteo-control, German	MOS (model Output Statistics) by Meteomedia GmbH	ECMWF - 0.25°x 0.25° - 3 hours
Ciemat, Spain	Bias correction	AEMet-HIRLAM - 0.2°x 0.2° - 1 hour
CENER, Spain	Post-processing based on learning machine models	Skiron/GFS - 0.1°x 0.1° - 1 hour
Meteotest, Switzerland	Direct model output of global irradiance, averaging of 10x10 pixels	WRF/GFS - 5km x 5km - 1 hour
University of Jaen, Spain	Direct model output of global irradiance	WRF/GFS - 3km x 3km - 1 hour

stage of research, irradiance forecasts based on global model numerical weather prediction models in combination with post-processing show best results. All proposed methods perform significantly better than persistence.

In addition to the benchmarking studies for Europe, SUNY and Natural Resources Canada (Canmet ENERGY) are continuously evaluating forecasts at high-quality ground stations in the U.S. and Canada (see, e.g., the paper by Perez et. al presented at Solar 2009). In addition to some of the forecast models shown in Figure 6.13, the U.S. is evaluating the National Digital Forecast Database (NDFD). In addition, three forecasting algorithms were benchmarked in Canada for three ground stations over a one-year period (June 1, 2009 to May 31, 2010). As with the European forecasts, global numerical weather prediction models performed best, with RMSEs on the order of 30 to 40%, intermediate between the Spanish and Central European results. It was found that averaging of the results of different algorithms lead to a slight reduction in errors. The results, shown in Figure 6.14, were presented at EuroSun 2010.

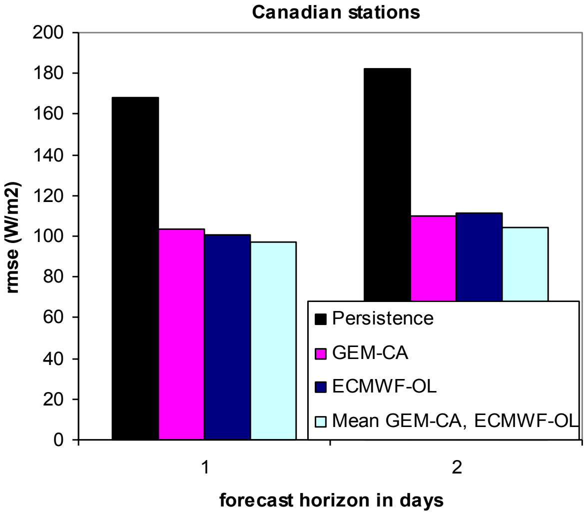

Figure 6.14 Average root mean square deviation $RMSD_{60min}$ for three Canadian ground stations for +24 h and +48 h ahead forecasts.

In addition to the benchmarking exercises, all Task members involved in irradiance forecasting are continuously working on further development of the forecasting algorithms for forecasting global irradiance. Some institutes (DLR; University of Jaen, University of Oldenburg) have also started or continued research in direct irradiance forecasts. Due to the nature of DNI, it is much more difficult to predict beam irradiance.

Furthermore different forecast applications are under study, e.g., power forecasting for PV systems and solar thermal power plants, or use of forecast information for load management for the integration of a solar thermal power plant into an existing district heating grid. A short overview of the forecasting activities of the different task members is given below.

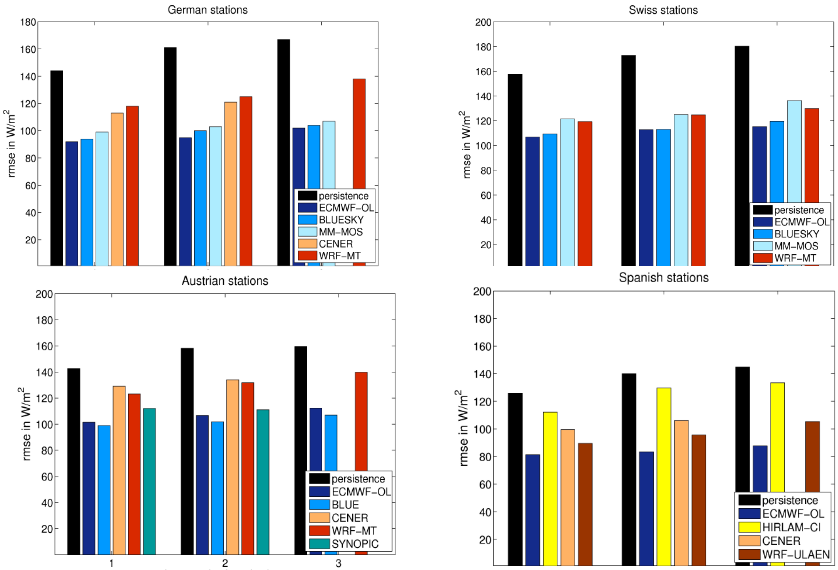

Figure 6.13 $RMSD_{60min}$ for +24 h, +48 h and +72 h forecasts for stations in Germany (GHI_{mean}=227 W/m^2), Switzerland (GHI_{mean}=267 W/m^2), Austria (GHI_{mean}=222 W/m^2), and Spain (GHI_{mean}=391 W/m^2).

DLR started a feasibility study in collaboration with Solar Millennium AG on the use of Earth observation and satellite communications in a forecasting system for Concentrating Solar Power (CSP) plants, such as Andasol (Kraas, et al., 2010). The work is co-funded by the European Space Agency ESA in its Integrated Application Program (IAP).

6.4 Links with Industry

Several small companies are participating directly in the Task: Blue Sky Wetteranalysen, Meteotest AG, Suntrace GmbH, and recently a company formed by two Task Participants, GeoModel. s.r.o. Another Task Participant has formed a cooperative arrangement with Clean Power Research in the U.S. to market satellite-derived data. The audience for the results of Task V includes the technical laboratories, research institutions, and universities involved in developing solar resource data products. More importantly, data users, such as energy planners, solar project developers, architects, engineers, energy consultants, product manufacturers, and building and system owners and managers, and utility organizations, are the ultimate beneficiaries of the research, and will be informed through targeted reports, presentations, web sites, handbooks and journal articles.

6.5 Conclusion and Next Steps

Since its start in 2005 the IEA Task "Solar Resource Knowledge Management" has led to several successful national and international research, development and demonstration projects. It has significantly improved international collaboration, which helped shorten development cycles in this field. New satellite methods were developed and existing algorithms improved. Recently, the quality of beam irradiance products was significantly improved. However, a congruent validation of DNI data is still missing. This will be ready by 2012 under the new SolarPACES DNI benchmarking project.

Several methodologies for solar radiation forecasting are under development. Most provide global radiation data, but some prototypes also now offer beam irradiance data, which will be extremely important for future operation of CSP plants.

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7 Task VI:
Solar Energy and Water Processes and Applications

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- Reda Abdel Azim Younes (NREA, Egypt)
- Craig Turchi (NREL, USA)

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 by 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.

The Scope of Work defined for 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.

The purpose of the Task is therefore to improve the conditions for introducing solar water treatment on the market and solve water problems, while reducing 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 Participation and National Contributions in 2010

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 active participants are Egypt, Germany, Mexico, South Africa, Spain and United States.

Ongoing Task VI activities are presented in Table 8.1, following the structure above. In the sharing column, "I" refers to information sharing; "M" to task sharing by member countries, "T" to task sharing trough SolarPACES; and "C" to cost sharing. Main SolarPACES contact person is indicated.

The most important achievements in 2010 with up-to-date information about project participation, objectives, status, and relevant publications, are summarized below.

7.4 Summary of achievements

7.4.1 Concentrating solar power and Desalination Plants

Assessment of CSP+D potential in the MENA area

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Duration: April 2010 – March 2011

Participants: CIEMAT, DLR, NREA

Funding: 25 k€ from SolarPACES

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

Purpose: The purpose of this project is 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. This study was combined with the DNI assessment in the

Table 7.1 Summarized Task VI reported activities organized by Sector

Sectors and Activities	**Contact**	**Sharing**			
		I	**M**	**T**	**C**
Sector 1. Concentrating solar power & Desalination Plants					
CSP+D potential at MENA countries	J. Blanco			x	
CONSOLI+DA	J. Blanco		x		
Sector 2. Solar Thermal Desalination Systems					
MEDIODIA	J. Blanco		x		
WESS	A. J. Vazquez	x			
MEDESOL	J. Blanco		x		
Sector 3. Solar water detoxification and disinfection					
SOWARLA	C. Jung		x		
SOLPUR	C. Jung		x		
SODISWATER	P. Fernández		x		
INNOVATECH	S. Malato		x		
TRAGUA	B. Sánchez		x		
EDARSOL	S. Malato	x			

coastal strip of Egypt, selecting one specific location and carrying out a first preliminary design and economic study of an integrated CSP+D plant on the site.

Achievements in 2010: Solar radiation was estimation from satellite images by IRSOLAV (Spain) based on a functional relationship between the solar irradiance at the Earth's surface and the cloud index estimated from the images. This relationship was fitted using high quality available ground data in such way that the solar irradiance-cloud index correlation can be extrapolated to any location of interest. Radiation (global and DNI) was estimated 5 km away from the sea (to avoid the albedo effect of the sea as much as possible) and at intervals of 10 km.

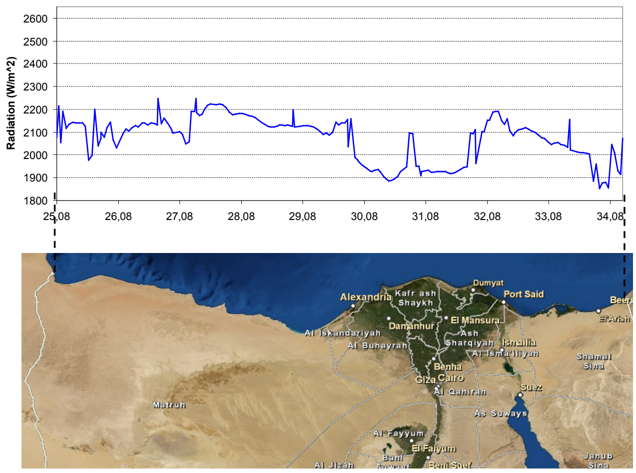

Figure 7.1 Yearly average DNI on the Egyptian Mediterranean coast

DNI on the Egyptian Mediterranean coast ranged from 1854 to 2247 kWh/m^2 year (Fig. 1). On the Egyptian Red Sea coast, it was from 2082 to 2611 kWh/m^2 year. In addition, the following CSP+D configurations were analyzed thermodynamically:

- 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 different possible low pressure steam extractions from the turbine.
- RO (reverse osmosis) unit connected to a PT-CSP plant.

In all cases studied the freshwater and electricity production considered is the same (40.520 m^3/day, 50 MW$_e$, respectively). The results are valid for arid regions where RO has higher specific electricity consumption and dry cooling is used in CSP plants.

The selected location for the preliminary CSP+D study was Port Safaga on the Egyptian Red Sea with where estimated DNI is 2,496 kWh/m^2 year. A 14-hour molten salt thermal storage system was considered. Another hypothesis was for the desalination unit to work fully associated with the CSP plant (if stopped the desalination plant is also).

Table 7.2 Net thermal capacity output required, overall CSP+D efficiency and aperture area resulting from each desalination configuration proposed for the Port-Safaga location (Egypt), considering 50 MW$_e$ and 40520 m^3/day power and net water production, respectively

Desalination system	Net thermal capacity output required (MW$_{th}$)	Overall efficiency (%)	Aperture area (m^2)
LT-MED	183	27.4	461,070
LT-MED-TVC	228	22.0	574,430
RO	193	25.9	487,230

The results showed slightly better combined efficiency of CSP-LT-MED over CSP-RO and smaller solar field (Table 7.2). However, when the levelized energy and water costs are estimated (Table 3), the differences are very small.

Table 7.3 Comparative levelized costs of power (50 MW$_e$ net production) and water (40.520 m^3/day net production) cogeneration with PT-CSP/RO and PT-CSP/LT-MED configuration at Port-Safaga (Egypt)

Cogeneration system	Investment solar plant (M€)	Investment desalination plant (M€)	LEC (€/kWh)	LWC (€/m^3)
PT-CSP / RO	321.46	34.49	0.156	0.678
PT-CSP / LT-MED	317.50	42.59	0.154	0.735

Publications:

[7.01] Blanco J., Alarcón D., Zaragoza G., Guillén E., Palenzuela P., Ibarra M. (2010) Expanding CSP research frontier: Challenges to be addressed by Combined Solar Power and Desalination plants. In: SolarPACES 2010. The CSP Conference: Electricity, Fuels and Clean Water from Concentrated Solar Energy. 21-24 September 2010, Perpignan, France

CONSOLI+DA – Consortium of Solar Research and Development

Contact:	Julián Blanco Gálvez, PSA-CIEMAT julian.blanco@psa.es
Participants:	20 Spanish Companies and 18 subcontracted Spanish Research Institutions;
Funding:	24 M€ from the 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

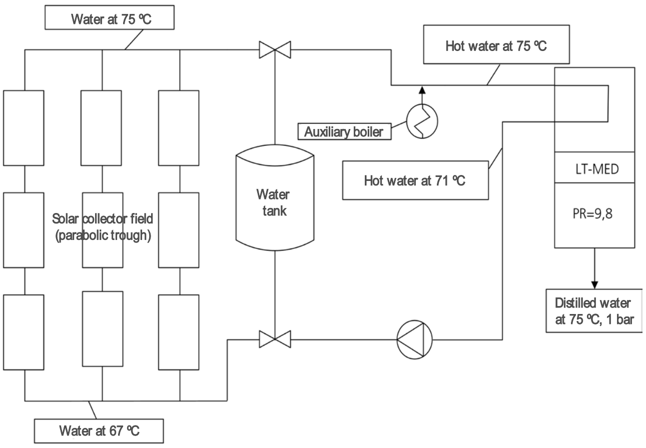

Figure 7.2 Scheme of Low Temperature Multi-Effect Distillation system coupled to a parabolic trough collector field

CSP can effectively contribute to the achievement of EU targets in energy policies, such as the 20% reduction in carbon dioxide emissions by 2020, it is reasonable to expect the growing importance of project development not only in Spain, but also in other countries. The main purpose of this project is therefore to consolidate the leading position of Spanish companies in the field of concentrating solar power.

Purpose: The PSA-CIEMAT Department of Environmental Applications of Solar Energy participates in the particular branch of the project which concerns desalination, for the general purpose 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 solar collection and desalination technology options; (ii) to perform technical and economic analysis of the different combined options; and (iii) to analyze those options in depth by conceptual predesign of specific plants.

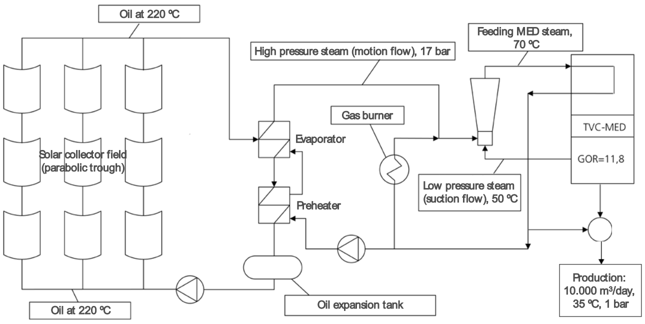

Figure 7.3 Scheme of Low Temperature Multi-Effect Distillation with Thermal Vapour compression system coupled to a parabolic trough collector field

Achievements in 2010: Computer models of selected and defined CSP+D configurations were developed for LT-MED (low temperature multi-effect distillation) and LT-MED-TVC (low temperature multi-effect distillation with thermal vapour compression). These models included thermal storage to increase the solar fraction of the combined power and desalination plant and also fossil fuel hybridization to guarantee continuous 24-hour operation. With the help of this software, the solar collector field and desalination system were designed and sized considering different power and water production capacities (Figure 7.2 and Figure 7.3).

Publications:

[7.02] Palenzuela P., Alarcón D., Blanco J., Zaragoza G., Guillén E., Ibarra M. (2010) Steady-State Mathematical Modeling of a Solar Multi-Effect Desalination Plant at the Plataforma Solar de Almería. In: EuroMed 2010 Desalination for Clean Water and Energy. 3-6 October 2010, Tel Aviv, Israel.

7.4.2 Solar Thermal Desalination Systems

MEDIODIA – Multiplication of Efforts for the Development, Innovation, Optimization and Design of Advanced Greenhouses

Contact: Dr. Julian Blanco, julian.blanco@psa.es
Duration: January, 2007-December 2010
Participants: Repsol YPF (E); Acciona Solar (E) (CIEMAT-PSA as subcontracted); Ulma Agrícola (E); Ulma Packaging (E); Acciona Agua (E); Ulma Handling Systems (E); Fundación Cajamar (E); Agrobio (E); Biomiva (E); Grupo AN (E); Ingeteam (E).
Funding: 25 M€ by Spanish Ministry of Industry, Tourism and Trade (INGENIO Programme CENIT Project);

Background: Intensive agriculture is one of the major agricultural sectors in Spain. Advanced R&D are needed to place Spain on the front line in agro-food technology. The results will not only be useful in the agro-food sector, but will boost other industrial activities and services.

Purpose: The main objective of this project is to develop a new concept for an advanced highly-automated greenhouse, with efficient water and energy consumption to allow diversified and profitable growing under all climate conditions in Spain.

The contribution of the PSA-CIEMAT focuses on two main objectives:

i) Building and evaluation of a medium temperature parabolic trough collector for different thermal applications
ii) Possible connection of this PTC collector to an organic Rankine cycle in polygeneration schemes (electricity, refrigeration, water, heat).

Figure 7.4 Photo of the new PTC solar field in operation at the PSA

Achievements in 2010: A 125-kW_{th} solar field with eight parabolic-trough collectors was designed, purchased and installed for evaluation of its application in different polygeneration and desalination schemes. The collector selected was the Polytrough 1200 prototype, designed by the Australian company, NEP Solar. It has a theoretical nominal efficiency of 55% working at 120-220ºC for 1000W/m^2 direct beam solar radiation. The nominal power is 15.8 kW per collector at an average temperature of 200ºC. Evaluation testing has already started and the results so far show the collector is able to reach and maintain the temperatures required for integration in the schemes studied. Therefore, the field has the potential for use as a thermal energy source in systems where medium-temperature heat is needed, such as polygeneration or desalination systems.

Water Evaporation of Salt Solutions (WESS)

Contact: Alfonso J. Vázquez[1], avazquez@cenim.csic.es
Participants: CENIM
Funding: own funding

Salt production has been common all over the world for a long time. Today, different salt components are obtained by fractionated crystallization in salt mines in many places, mainly in Chile, Peru and Bolivia. In particular, salt in Bolivia has a large amount of LiCl that is a promising source of Li for applications in batteries with a high expected demand for electric cars.

The traditional procedure is simply to expose large surfaces of water to natural evaporation under strong solar radiation and fairly good winds.

The evaporation is due more than to the temperature on the surface of the pond, to wind and air humidity, which in the Chilean deserts is very low. So evaporation slows down when the wind is low. But as it happens, the desert winds are strong enough to maintain evaporation at a fairly good rate.

Although the solution temperature is also important, it is not very high, because the solution is transparent to solar radiation. The bottom and sides of these ponds are usually black to ensure all the solar radiation is captured by the solution. But the amount of mass is so large that the pond temperature is very low.

To increase the surface temperature of the water, we placed a floating sheet a few centimeters from the top. The sheet was smaller than the size of the pond, dividing it into two communicating volumes, as seen in Figure 7.5.

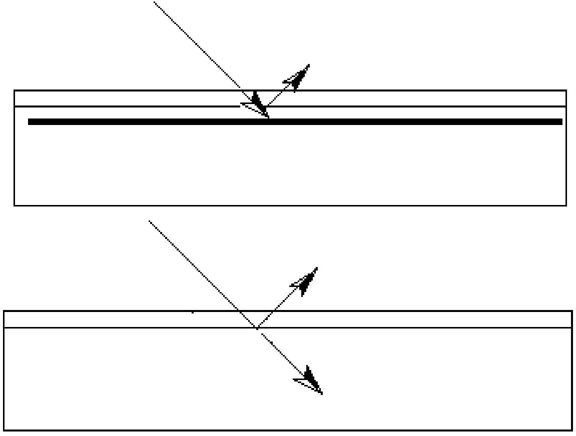

Figure 7.5 Top: traditional evaporation pond. Bottom: evaporation with a single floating sheet under the free water surface

This way the radiation heats only the small amount of mass on top of the sheet, increasing the temperature several degrees above the normal temperature in the pond. The result of this increased temperature is that the vapor pressure rises, and thereby, the evaporation rate.

Our tests were performed at lab scale but the data obtained demonstrate a clear increase in evaporation rate. Table 7.4 shows the data obtained under the free surface dividing the pond into two communicated parts.

It may be seen that the temperature rose only from 4 to 7.5ºC, but this was enough to increase the evaporation rate 16% in the two small ponds installed side by side at the CENIM.

At the present time, we are testing a new system to enhance the water evaporation of salt solutions even more. This new procedure consists of a flat collector heating the salt solution. The heated solution is poured on a large surface such as that of a pond maintaining water at a minimum depth.

The salt solution is expected to be heated up to 80ºC by solar energy. At this temperature the vapor pressure is much higher and, consequently, the evaporation rate will also be even higher.

The state of the surface will be also considered as a parameter to increase the effective evaporation surface.

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[1] Vázquez, A.J., Vargas, T. Spanish Pat. Nº P200931215

MEDESOL – Seawater Desalination by Innovative Solar-Powered Membrane-Distillation System

Participants:	CIEMAT-PSA (E); Univ. La Laguna (E); Acciona Infraestructuras (E); ACUAMED (E); AO SOL (P); Univ. Stuttgart (D); Tinep (MEX); National Autonomous Univ. Mexico (MEX); Royal Institute of Technology (S); Scarab AB (S); Iberinsa (E).
Contact:	Julián Blanco, PSA-CIEMAT, julian.blanco@psa.es
Funding:	EC-funded project, cost-shared: 1,385 k€
Duration:	October 1, 2006 - March 31, 2010

Background: There is a consistent lack of effective, robust small-to-medium-scale desalination processes. Such technologies are needed mostly in remote areas, typically located in arid or semi-arid zones, and therefore, development of renewable energy desalination processes must be considered highly desirable. Solar thermal membrane distillation seems to be a promising option for filling this gap.

Purpose: (i) Study membrane distillation to improve its efficiency, (ii) develop effective heat-recovery concepts; (iii) develop system components, e.g., a solar collector optimized for the target working temperatures (80-100ºC) and a non-fouling coating for the heat transfer surface, (iv) develop complete medium (a few m^3/day) and small-capacity systems (several hundred L/day).

Achievements in 2010: (i) a complete solar membrane distillation plant was designed using the SCARAB AGMD module. (ii) The economic analysis was done, considering different solar collectors to provide the thermal energy, different specific thermal consumptions and different MD module costs. Water costs achieved were very disparate, ranking from 6.22 to 76.17€/m^3 of fresh water produced.

Table 7.4 *Experimental data on evaporation with (Yes) and without (No) sheet under the free water surface*

Sheet	Test time h	Temp. C	Level-change mm	Evap. yield l/h·m^2	Yield %	Mean Evap. yield l/h·m^2
Yes	24	29	8.22	0.125	4	16.0
No		21.5	7.91	0.120	-	
Yes	24	27	8.25	0.125	26.1	
No		21	6.53	0.099	-	
Yes	72	30.5	22.25	0.337	15.8	
No		24.5	19.22	0.291	-	
Yes	24	27	6.98	0.106	20.9	
No		23	5.77	0.087	-	
Yes	24	26	5.22	0.084	13.4	
No		21	4.87	0.074	-	

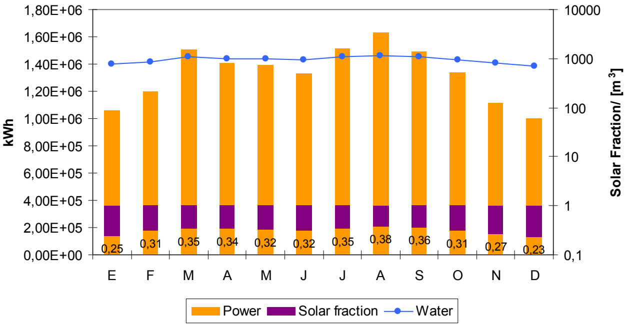

Figure 7.6 *Power input needed, solar fraction and water production in a 100 m^3/day solar desalination plant using the SCARAB module and AOSOL CPC solar collector*

(iii) Some additional project conclusions were: a) Distilled water production ratio by MD technology is still very low. SCARAB technology, with 2,8 m^2 of membrane per module, produce about 3,8 litres of distilled water per hour and square meter of membrane (by contrast, current Reverse Osmosis technology typically produces about 14 L/m^2h), and very far from the reported results achieved at (very small) lab scale (80 L/m^2h at 60ºC); b) Distillate production is very low when operating temperatures are below 80 ºC, meaning that energy consumption significantly increases, so the practical range of operating temperatures is not so high than indicated in the literature.; c) Specific thermal energy consumption affects linearly to the cost of the produced water, being therefore very important to achieve effective internal energy recovery into MD modules; d) The combination of three factors: MD technology cost reduction, specific thermal energy consumption reduction and water production ratio (per m^2 of membrane) increase, is considered critical to commercial viability achievement.

Figure 7.7 *AOSOL CPC solar collector developed for the MEDESOL project*

Publications:

[7.03] Guillén E., Blanco J., Alarcón-Padilla D., Zaragoza G., Palenzuela P., Ibarra M. (2010) Preliminary assessment of a solar energy driven membrane distillation system. In: EuroMed 2010 Desalination for Clean Water and Energy. 3-6 October 2010, Tel Aviv, Israel.

[7.04] E. Guillén, J. Blanco, D. Alarcón, G. Zaragoza, P. Palenzuela, M. Ibarra, Comparative evaluation of two membrane distillation modules. Desalination and Water Treatment. Accepted (2010).

[7.05] E. Guillen et. al. Experimental analysis of an air gap membrane distillation solar desalination pilot system. Journal of Membrane Science. Submitted (2010)

7.4.3 Solar water detoxification and disinfection systems

Solar Water Treatment for the DLR Site Lampoldshausen - SOWARLA

Contact: Christian Jung, christian.jung@dlr.de
Duration: April 1, 2005 – January 31, 2010
Participants: Hirschmann Laborgeräte GmbH&Co.KG (D), Deutsches Zentrum für Luft- und Raumfahrt e.V. (D); KACO new energy GmbH (D)
Funding: 779 k€; Deutsche Bundesstiftung Umwelt (D)

Background: At the DLR Lampoldshausen site, space propulsion engines are tested in large-scale test facilities. Huge amounts of water are needed for cooling during the tests, most of it contaminated with different compounds in low concentrations. These compounds are mostly unburned rocket fuels (hydrazine and its derivates) or reaction products like nitrite. The purpose of the SOWARLA research project was to install a solar water treatment plant in addition to the existing water treatment plant working with classic UV-oxidation technology to enlarge the water treatment capacity of the site.

Purpose: After five years of development, a new industrial solar water treatment plant based on a photo-Fenton concept has been commissioned. The solar water treatment plant installed is designed to treat all of the contaminated water from the test facilities in the summertime while the existing UV oxidation plant can be used as a backup system or in wintertime. With the new solar plant, the water treatment costs will be significantly lower, because large amounts of chemicals and energy can be saved in comparison to the current treatment procedure with UV oxidation.

Figure 7.8 The solar photocatalytic water treatment demonstration plant in Lampoldshausen, Germany

The solar water treatment plant is comprised of the solar receiver with a 238 m² aperture area and the fluid handling and control system. The solar plant control is connected to the UV oxidation control system and is fully automatic. The iron catalyst is separated and reused. The water is treated independently of the contaminant concentration, reaction kinetics and irradiance, based on experimental results with a prototype receiver and on-site solar irradiation pyranometer measurements.

Achievements in 2010: The solar water treatment facility was handed over to the DLR Institute of Space Propulsion in Lampoldshausen as the future operator of the plant. Besides routine plant operation, accompanying research was done to characterize the system and evaluate operating procedures. It was demonstrated that the catalyst recycling and reuse system, and the concentration and irradiation dependent control procedures work as predicted.

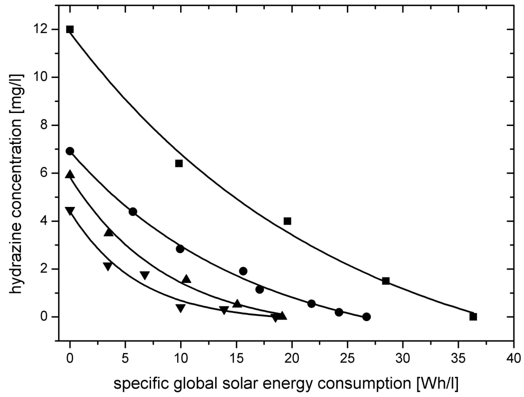

Figure 7.9 Decontamination of wastewaters of different hydrazine concentrations (and different irradiation conditions) by the demonstration plant in automatic operation mode

Publications:

[7.06] C. Jung, et al., Decontamination of Cooling Water from Space Propulsion Testing by Solar Light Enhanced Fenton Treatment. The 16th International Conference on Advanced Oxidation Technologies for Treatment of Water, Air and Soil (AOTs-16), 15 – 18 October 2010, San Diego, USA..

[7.07] C. Jung, et al., The Non-Concentrating Solar Photocatalytic Water Treatment Plant in Lampoldshausen, Proceedings of the 16th SolarPACES Conference, 21 - 24 September 2010, Perpignan, France.

[7.08] C. Sattler et al.., Solar Photocatalytic Detoxification of Rocket Test Facility Waste Water with a Non Concentrating Tubular Receiver (NCTR) Pilot Plant, 14th Biannual SolarPACES Symposium 4 – 7 March 2008, Las Vegas, USA.

Development of glass tube coatings for solar photocatalytic water treatment applications - SolPur

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:	513k€; 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 can not 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 lead to lower pump energy and very simple fluid installations for solar photocatalytic water treatment.

Purpose: In this project, commercially available formulations were applied to build up TiO$_2$ coatings inside glass tubes as receiver elements for photoreactors. After screening 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 2010: The photocatalytic activity of glass tube coatings was checked by decolorization of methylene blue under UV-A irradiation and isothermal conditions in a laboratory test set-up.

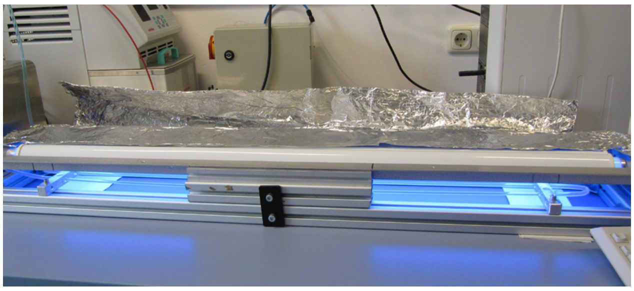

Figure 7.10 Laboratory test set-up for photocatalytic activity of coated glass tubes (recirculation system with online analysis by photometer recirculation bypass)

With a test loop of four tubes connected in series, more than 90% decolorization was achieved under standardized conditions.

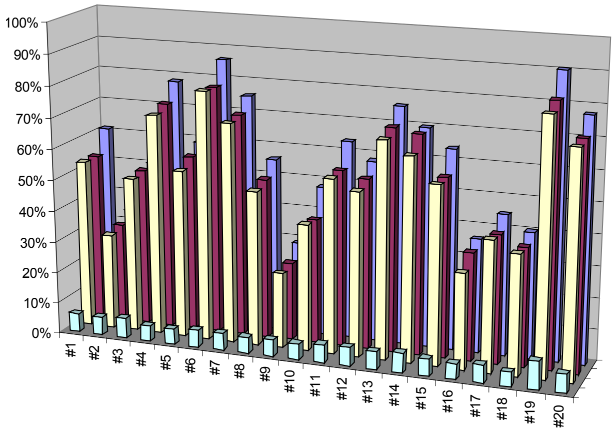

Figure 7.11 Decolorization of methylene blue with TiO2 coated glass tubes in the laboratory set-up (green: no UV-A, blue: 1st run; purple: 2nd run; yellow: 3rd run)

Repeated methylene blue degradation tests with the best coating revealed initial activity losses over ~10 runs, but no significant deactivation of the coating could be decided within the experimental uncertainty until over 50 runs.

Degradation of the antibiotic sulfamethoxazole led to concentrations below the HPLC-DAD detection limit (<10 µg/l) in the laboratory test.

In presence of excess amounts of non-ionic surfactants, sulfamethoxazole elimination was observed to be slower as expected from the competing degradation. After catalyst washing with diluted sulfuric acid, photocatalytic activity was observed to be the same as before the surfactant test.

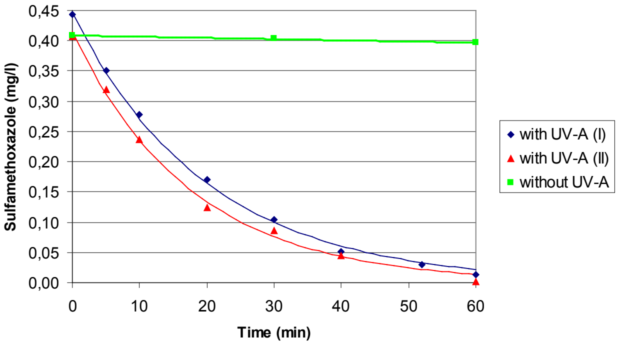

Figure 7.12 Degradation of sulfamethoxazole in the laboratory set-up

Solar Disinfection of Drinking Water for Use in Developing Countries or in Emergency Situations -SODISWATER

<u>Contact</u>: Kevin G. McGuigan, kmcguigan@rcsi.ie
Pilar Fernández, pilar.fernandez@psa.es
<u>Duration</u>: September, 2006 – February, 2010
<u>Participants</u>: Royal College of Surgeons in Ireland (IE), Univ. Ulster (UK), Council for Scientific and Industrial Res. (ZA), Swiss Federal Inst. of Aquatic Sci. and Tech. (CH), Inst. of Water and Sanitation Dev. (ZW), CIEMAT-PSA (E), Univ. Leicester (UK), Int. Community for the Relief of Suffering and Starvation (KE), Univ. Santiago de Compostela (E).
<u>Funding</u>: 1,900 k€; EC funded project, cost shared (FP6-2004-INCO-DEV-3)

<u>Background</u>: Through a combined biocidal effect of temperature and UV irradiation, solar disinfection (SODIS) has been shown to inactivate a broad range of important waterborne disease-causing pathogens. This inactivation process has been shown to be effective for contaminated water contained in transparent containers (⩽ 2L plastic bottles) which are exposed to sunlight for 6 hours. However, there remains a need to generate a larger volume of disinfected water at a given time as well as ensuring adequate inactivation of bacteria during low sunlight and ambient temperature conditions.

<u>Objectives</u>: The main objective of this project is the development of an implementation strategy for the adoption of solar disinfection of drinking water as an appropriate, effective and acceptable intervention against waterborne disease for vulnerable communities in developing countries without reliable access to safe water, or in the immediate aftermath of natural or man-made disasters.

<u>Achievements in 2010</u>: During this year, CIEMAT completed several tasks in collaboration with the University of Santiago de Compostela, testing new advanced oxidation processes for water disinfection based on hydrogen peroxide and iron salts in the presence of solar radiation. We have tested different solar photoreactors on *Escherichia coli, Cryptosporidium parvum*, and *Fusarium* as model resistant water pathogens under natural sunlight and water conditions. The experiments were performed under natural solar radiation at the Plataforma Solar de Almería. Two 2.5-L borosilicate glass tubes were filled with water with turbidities of 0, 5, and 100 NTU, spiked with 5×106 purified *C. parvum* oocysts, and placed in two CPC systems, CPC1 and CPC1.89 which have concentration factors of 1 and 1.89, respectively. The results with CPC1 showed that in an exposure time of 2 h, there was a significant decrease in overall viability in water with 0 and 5 NTU of 14.3% and 8.7%, respectively. After 6 h of exposure time (first day) the overall viabilities were 3.9% and 4.9% for water with turbidity of 0 and 5 NTU, respectively, and almost zero at the end of the test. For water with a turbidity of 100 NTU, the overall viability showed a significant decrease after 4 h of exposure time (8.1%). The overall viability was zero at the end of the test (Figure 1). The employ of CPC1.89 showed a similar inactivation pattern to CPC1. After 6 h of exposure time, the global viabilities were 4.0%, 4.0% and 10.7% for turbidity levels of 0, 5 and 100 NTU, respectively. On the second day of exposure, the overall viabilities were practically zero for all turbidities assayed (Figure 7.13).

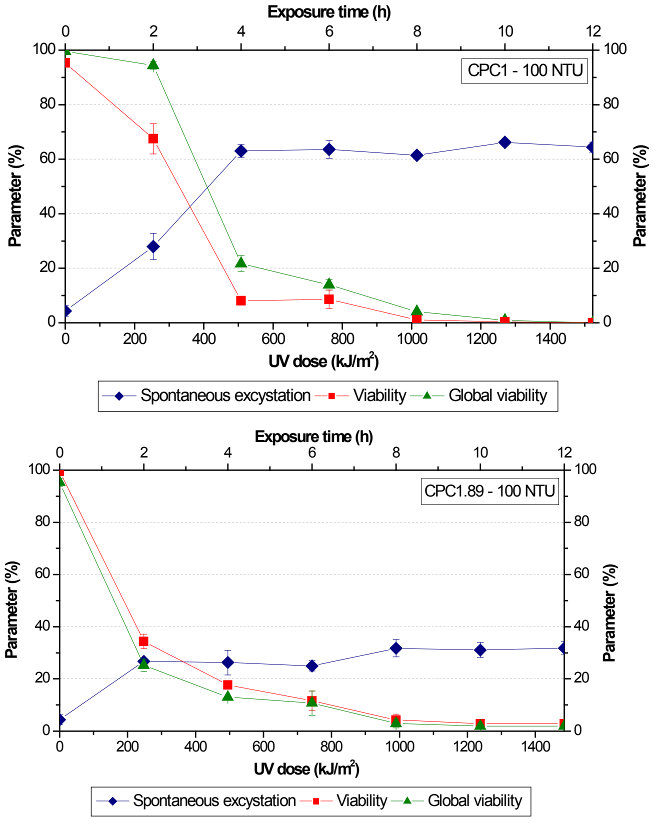

Figure 7.13 Inactivation kinetics of C. parvum oocysts suspended in water samples with different turbidity and exposed to real sunlight in CPC1and CPC1.89 2.5- L compound parabolic concentrators

This study is the first study that evaluates the thermal contribution in the survival of *C. parvum* during SODIS, independently of the UV radiation, showing a significant contribution in the inactivation of *C. parvum* oocysts during SODIS under natural sunlight. This year we studied the feasibility of a sequential batch solar photoreactor based on the effect of solar radiation. The new system ('sequential batch system') permits the continuous treatment of contaminated water using an automatic valve which empties the system once the water is decontaminated. Therefore, the volume of contaminated water that could be treated is higher than with the classical SODIS bottles since the system refills the irradiated CPC+tubes modules automatically every time the water inside is free of pathogens.

Publications:

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Innovative and Integrated Technologies for the Treatment of Industrial Wastewater - INNOWATECH

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Funding: 2,750 k€. EC funded project, cost-shared (FP6, subpriority 6.6.3 Global Change & Ecosystems)

Background: New concepts and processes in industrial wastewater treatment with high potential benefits for the stable quality of effluents, for saving energy and operating costs and for environmental protection, which is the goal of the EU Environmental Technologies Action Plan.

Objectives: Development of aerobic granulation bioreactors, combining Advanced Biotreatment and Advanced Oxidation Processes, new membrane processes, Life Cycle Assessments and Life Cycle Costs. CIEMAT focuses on further development of solar photo-Fenton treatment for integration with aerobic biological treatment.

Achievements in 2010: The industrial-scale combined photo-Fenton/IBR system was able to successfully decontaminate real wastewater from washing pesticide containers. In addition, the composition of the real wastewater was determined by LC-MS-TOF using an accurate-mass database (about 300 compounds in 20 minutes). Two other studies were also performed: (i) the effect of saline effluent conditions (SO_4^{2-} and Cl^- in the typical range of concentrations found in natural water, 50 – 2000 mg/L, influence of NaCl at 5 g/L and seawater conditions at 35 g/L of NaCl and (ii) formation of halogenated degradation by-products were analyzed by LC-MS-TOF under saline effluent conditions with photo-Fenton treatment. The main outputs of the project have been: (i) when treating complex wastewater (e.g., mature municipal landfill leachates or pharmaceutical WW), the integration of

Table 7.5 Efficiency of the combined system photo-Fenton/ biotreatment for removal of pesticides in real wastewater

Compound	% Reduction combined system	Final conc (µg/L)
Imidacloprid	96.4	25
Dimethoate	99.4	5
Pyrimethanil	42.7	485
Thiacloprid	84.2	88
Azoxystrobin	99.4	3
Malathion	100	< 0.1
Carbofuran	100	< 0.1
Metalaxyl	100	< 0.1
Spinosyn a	100	< 0.1
Bupirimate	100	< 0.1
Fenamiphos	100	< 0.1
Tebufenozide	100	< 0.1

biological and chemical treatments results in synergistic effects which save on costs and increase the effectiveness of the overall treatment; (ii) it is feasible to make use of sunlight in photochemical reactors, saving chemicals and energy in treatment of wastewater containing toxic pollutants; (iii) innovative methods for immobilizing (and/or recovering) photocatalysts on the surface of commercial polymers have been developed, implemented, and are now available; (iv) definition and testing of conceptual models of existing treatment systems and assessment of suitable software for LCA and LCC modeling and calculations have made it possible to compare the sustainability of the technologies studied.

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Treatment and Reuse of Waste Waters for Sustainable Management – TRAGUA

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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 has the highest water deficit in Europe, and only 5% of the waste water is reused. The reasons so little water is reused are diverse, but the most important is the lack of treatment protocols for treated water from Municipal Wastewater Treatment Plants (MWTP) and the lack of clear criteria for choosing technologies.

Purpose: A five-year project (2006-2011) for enhancing wastewater reuse in Spain. When completed, the program will provide an inventory of treatment protocols for potential reuse of waste water, according to its characteristics and the economically optimized technologies available, standard methods of chemical, microbiological and toxicological analysis, information about the impact of water on the environment and the respective socio-economic analysis.

Achievements in 2010: Results of the photocatalytic activity showed the potential application of the immobilized TiO_2 system for the degradation of the 15 emerging contaminants selected in distilled water, synthetic water and simulated wastewater effluent. Two main aspects were undertaken in 2010 to optimize the photocatalytic system: i) detailed characterization of the immobilized system to establish a correlation between the chemical, physic and photochemical properties and ii) evaluation of the photocatalytic system behavior with real water, bearing in mind that the final objective of the project is the reuse of water for irrigation (greenhouses, golf courses, public gardens, etc). Therefore, wastewater with a 13 mg L^{-1} COD content from the secondary biological treatment of a municipal wastewater treatment plant (MWTP) located in El Ejido (Almería) was selected. The experiments were carried out in a series of parallel tubular rectors placed in the focus of CPC collectors (Figure 7.14). The variation in photocatalytic efficiency with reaction time was evaluated during five consecutive cycles. The results indicated that 53% of the selected compounds were totally degraded after 60 min. This percent increased to 73% for reaction times over 150 min. Only, antipyrene, atrazine, flumequine and carbamazepine were not totally degraded during the overall photocatalytic process. As expected, photocatalytic performance decreased after the fifth cycle, but even under these severe operating conditions, 60% of the compounds were destroyed. The characterization results showed that this behavior was mainly related to TiO_2 active sites being blocked by adsorbed species, such

Figure 7.14 Glass tube photocatalytic reactor in the focus of Compound Parabolic Collector.

as nitrated phosphates, sulfur or chlorinated compounds and not to the loss of active phase.

The results demonstrated the efficiency of the photocatalytic system developed in the project for the treatment of emerging contaminants in real water with solar irradiation. These results open the application of photocatalysis to the reuse of wastewater. It is important to mention that this technology is an attractive alternative to TiO_2 suspension systems, avoiding the expensive filtration required to eliminate the fine TiO_2 particles from the water. Evaluation of a hybrid (solar/lamp) photoreactor prototype (Figure 7.15) for the treatment of volatile organic and sulfur compounds contained in real air from the primary sludge treatment units was another important achievement. Immobilized photocatalysts were placed inside the reactor by specially designed asymmetric star polygon-shaped structures. Hybrid composites based on $SiMgOx/TiO_2$, glass slides or organic polymer based materials were tested at semi-pilot plant scale.

Figure 7.15 Photocatalytic reactor for the treatment of real polluted air from a wastewater treatment plant.

The efficiency of the photocatalytic system was demonstrated, especially when hybrid materials were selected. The excellent results under the severe plant operating conditions, with a variable concentration of pollutant and the simultaneous presence of several types of organic and inorganic compounds are promising. The capacity of the new system improves the performance of conventional systems in terms of photocatalyst lifetime and deactivation phenomena, delaying formation of SO_2 as an H_2S reaction by-product.

Publications**:**

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

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Funding:	Spanish Ministry of Education and Science (National R&D Program): 0.8 k€.

Background: Although there is information available about the possible treatment of pollutants with different technologies, it is also well-known that nonbiodegradable 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 is to design, to built-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 2010: Comparison and evaluation of different advanced oxidation processes (AOPs) for the treatment of WWTP inlet or outlet wastewater containing typical emerging contaminants by studying and optimizing the variables. Response surface analysis was applied to optimize the most significant operating parameters to be considered in the processes. These parameters are the initial concentration of hydrogen peroxide, the catalyst concentration, the initial concentration of contaminants, the solar radiation intensity and the working temperature. And finally, another achievement of the project was the design and construction of a solar electro-photo-Fenton system for the treatment of wastewater containing typical emerging contaminants.

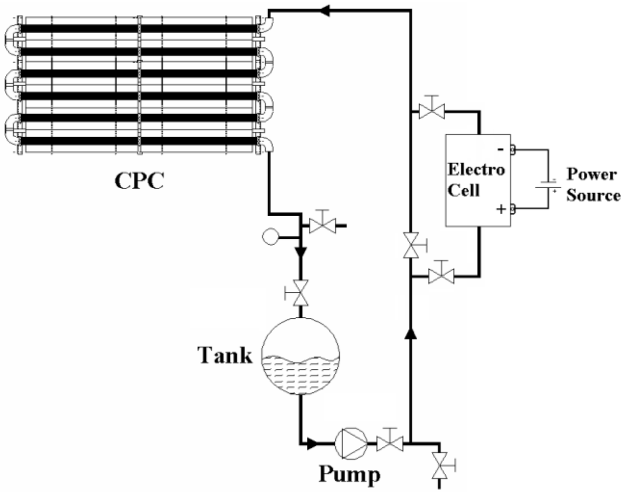

Figure 7.16 Solar pilot plant based on CPCs available at the PSA coupled to an electrochemical cell for solar electro-photo-Fenton

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7.5 Meetings

The 4th Annual Task VI Meeting was held in Perpignan (France), on September 20, 2010, just before the International SolarPACES Symposium at the same location. The meeting was attended by 12 representatives from six SolarPACES countries (Egypt, Germany, Mexico, South Africa, Spain and the United States). 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.

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