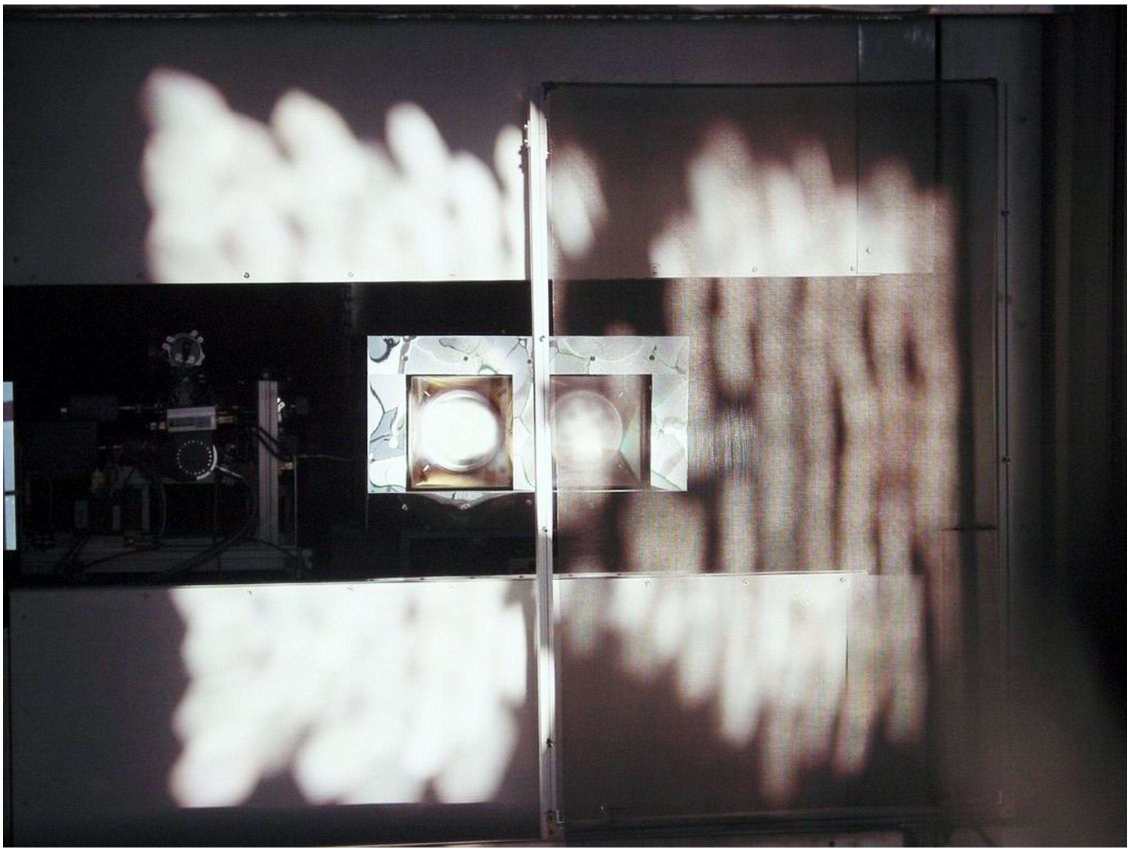
International Energy Agency (IEA)

Solar Power and Chemical Energy Systems

SolarPACES

Annual Report 2007

Edited by M. Geyer
in cooperation with
J. Blanco, M. Mehos, A. Meier,
R. Meyer, C. Richter, W. Weiss



DLR

Deutsches Zentrum für Luft- und Raumfahrt e.V.

Cover picture:
HYDROSOL: Descartes Research Prize 2006 winning solar reactor for quasi-continuous hydrogen production in operation at the solar furnace, DLR, Cologne Germany
(Deutsches Zentrum für Luft- und Raumfahrt e.V. Köln/Germany)

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

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

Editors

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Tom Mancini
Chairman, SolarPACES
Executive Committee

Foreword

Hello All,

Interest in Concentrating Solar Power continued to increase in 2007 at an even faster rate than last year, if that is possible. Spain continues to be the “hot spot” for CSP development with PS 10 providing power to the grid and the construction of PS 20 started; construction of the Andasol plants well under way; and the announcement of plants in Extremadura. There was also the announcement of closure on a couple of projects in North Africa and Egypt has also made substantial progress on their project.

Perhaps, the most aggressive region for the increase in CSP development activities is in the Southwest United States. Acciona started operation of Nevada Solar One in May at their site south of Las Vegas. We are starting to see an increased level of activity in the U. S. in the issuing of Requests for Proposal by the utilities and the announcement of projects by developers. In addition to the pending 800 MW of dish Stirling systems in southern California, there were announcements of other CSP projects, all but one in California, that include: Solel -- 553 MW of trough plants; Ausra -- 477 MW of linear Fresnel systems (177 MW in Florida); and, in December, Arizona Public Service released an RFP for 250 MW of CSP power. Interest in CSP projects has also been expressed by utilities located in New Mexico, Utah, and Colorado.

In large part, CSP project development in the U. S. has been enabled by Renewable Portfolio Standards in the states and a 30% Investment Tax Credit (ITC) at the Federal level. Unfortunately, the ITC failed in the last Congress on an attempt to extend it beyond the end of 2008 for another 8 years. We have strong hope that this will be corrected by the current Congress but, until the ITC extended for a reasonable amount of time, announced projects and new ones will be difficult to realize.

In response to all of this development, SolarPACES is faced with the question of how we can best support developing projects around the world? As we have stated before, our role is to provide technical assistance to project developers as they address the technical and operational issues. At the same time, we need to balance the competing demands of project support with our responsibility to provide intellectually honest views on the status and performance of the various CSP technologies to the public. We also need to continue to provide the next- and future-generation technologies and approaches that will further reduce the cost of CSP-generated electricity and fuels. Keeping these sometimes competing factors in mind, SolarPACES will continue our outreach to industry and our efforts to define how best to work together.

Last, I want to thank the Executive Committee and Operating Agents for your support and good work during this past year. I especially want to thank Michael Geyer for all of his exceptional work as Executive Secretary for the last seven years and to wish him good luck in his endeavors in the world of project development.

Best Regards,

SolarPACES Chair

Table of Contents

List of Acronyms

AEE..............	Austrian Ministry of Transport, Innovation and Technology
ACC............	air-cooled condensers
AERONET....	Aerosol Robotic Network
AF................	Anular flow
ALG.............	Algeria
ANL.............	Argonne National Laboratory (USA)
AOP............	advanced oxidation process
APS..............	Arizona Public Service Co. (USA)
ASME	American Society of Mechanical Engineers (USA)
ASES............	American Solar Energy Society
AEST	Advanced Energy Storage Technology Program (AUS)
AUS	Australia
B	Belgium
BFE	Swiss Federal Office of Energy (CH)
BHR	Bahrain
BMU	Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (D)
BMZ.............	Ministry for Technical Cooperation and Development (D)
BOM............	Bureau of Meteorology of Australia
BOO............	Build Own Operate contract
BOP.............	= balance of plant
BSRN	Baseline Solar Radiance Network
BUL	Bulgaria
CA...............	California (USA)
CB	carbon black
CC	combined cycle
CCD............	Charge-coupled device
CDER	Centre de Développement des Energies Renouvelables (MRC)
CDM	clean development mechanism
CEA.............	Commissariat à l'Energie Atomique (F)
CEN.............	Commitée Européen de Normalisation
CENIM	Centro Nacional de Investigaciones Metalúrgicas (E)
CER	Certified emission reductions
CERT............	Committee on Energy Research and Technology (IEA)
CESI.............	Centro Elettrotecnico Sperimentale Italiano
CFD.............	computational fluid dynamics
CFE..............	Comisión Federal de Electricidad (MEX)
CH...............	Switzerland
CHP.............	combined heat and power
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)
CoR Deutsche Gesellschaft Club of Rome (D)
CPC............ compound parabolic collector
CPTEC .... Center of Weather Forecast & Climatic Studies (BRA)
CR5 Counter Rotating Ring Receiver Reactor Recuperator
CSES Center for Solar Energy Studies (LBY)
CSIC .... Consejo Superior de Investiación Científica (E)
CSIR............ Council for Scientific and Industrial Research
CSIRO......... Commonwealth Scientific and Research Organisation (AUS)
CSP............. concentrated solar power
CST .... concentrating solar technologies
CT .... computer tomography
CU .... University of Colorado at Boulder

D .... Germany
DG RDT ...... Directorate General Research Development and Technology (EC)
DG TREN .... Directorate General Transport and Energy (EC)
DISS............ Direct Solar Steam
DLR .... Deutsches Zentrum für Luft- und Raumfahrt e.V. (D)
DLR ISIS....... *Irradiance at the Surface derived from ISCCP cloud data*
DNI .... direct normal irradiation
DOE............ Department of Energy (USA)
DSG .... direct steam generation

E.................. Spain
EAWAG...... Swiss Federal Institute of Aquatic Science and Technology
EC............... European Commission
ECMWF ...... European Centre for Medium-Range Weather Forecasts
EGY .... Egypt
EIB............... European Investment Bank (EIB)
ENEA .... Agency for New Technology, Energy and the Environment (I)
ENSMP........ Ecole des Mines de Paris (F)
EPC............. engineering, procurement, construction
EPFL .... Ecole Polytec. Federale de Lausanne (CH)
EPS.............. Arizona Environmental Portfolio Standard (USA)
ESRI............. Environmental Systems Research Institute
ESTIA........... European Solar Thermal Industry Association
ET .... emission trading
ETH.............. Institute of Energy Technology (CH)
EU .... European Union
ExCo........... Executive Committee (SolarPACES)

F.................. France
5th or 6th FP 5th or 6th Framework Programme (EC DG RDT)

FEM .... Finite element method
Fhg-ISE........ Fraunhofer-Institut für Solare Energiesysteme in Freiburg (D)
FUSP .... University of Sao Paulo Foundation

GA .... General Atomics (USA)
GAS............. GMES Atmosphere Service
GEBA .... Global Energy Balance Archive
GEF .... Global Environmental Facility
GEO .... Group on Earth Observations
GEOSS .... Global Earth Observation System of Systems
GEWEX .... Global Energy and Water Cycle Experiment
GHI.............. global horizontal irradiance
GISS............. Goddard Institute for Space Science (NASA)
GMI............. Global Market Initiative
GMES.......... Global Monitoring of Environment and Security
GR............... Greece
GSFC .... Goddard Space Flight Center (NASA)
GUI.............. graphical user interface

ha................ hectare
HCE............. heat collection element (parabolic trough)
HFSS .... High Flux Solar Simulator (PSI)
HHV............. higher heating value
HIA .... Hydrogen Implementing Agreement (IEA)
HTF .... heat transfer fluid
HWE .... House of Water And Environment Palestine (PAL)

I.................... Italy
IA................. Implementing Agreement (IEA)
ICP .... Instituto de Catálisis y Petroleoquímica (E)
ICROSS .... International Community for the Relief of Starvation and Suffering (Kenya)
ICV .... Instituto de Cerámica y Vidrio (E)
IDAE .... Institute for Energy Diversification and Saving (E)
IDMP .... International Daylight Measurement Programme
IEA............... International Energy Agency
IFEED .... Internationales Forschungszentrum für Erneuerbare Energien e.V. (D)
IGARSS........ International Geoscience and Remote Sensing Symposium
IIE................. Instituto de Investigaciones Eléctricas (MEX)
IL.................. Israel
INCO........... International Cooperation Programme (EC)
INETI .... Instituto Nacional de Engenharia, Tecnologia e Inovação (P)
INM .... Spanish National Weather Service
INPE............. National Institute For Space Research (BRA)
INSPIRE........ Infrastructure for Spatial Information in the European Community
IPHE .... International Partnership for the Hydrogen Economy
IPR .... Intellectual property rights
IRR .... Internal rate of return
ISCCS.......... integrated solar combined-cycle system

ISES .... International Solar Energy Society
ISO .... International Standard Organization
ITW.............. Institut für Thermodynamik und Wärmetechnik (Univ. Stuttgart) (D)
IWSD .... Institute of Water and Sanitation Development (Zimbabwe)

J .... Japan
JI .... joint implementation
JOR............. Jordan
JRC .... Joint Research Centre (EC)

KEN .... Kenya
KfW .... Kreditanstalt für Wiederaufbau (D)
KJC .... Kramer Junction Company

LBY.............. Libya
LEC .... levelized electricity cost
LFR .... linear Fresnel reflector

MC .... Monte Carlo ray-tracing
MSM .... MAN Solar Millennium
MENA .... Middle East and North Africa
MEX .... Mexico
MONI.......... Ministry of National Infrastructures (IL)
MRC .... Morroco
MTBF........... Mean Time Between Failures
MWTP .... municipal wastewater treatment plants

N .... Norway
NAC .... new selective absorber coating
NASA.......... National Aeronautical and Space Administration
NASA LaRC Langley Research Center (USA)
NASA SSE ... Surface meteorology and Solar Energy
NC .... National Coordinator (Task 2)
NCTR .... non-concentrating tubular receiver
NEAL........... New Energy Algeria
NERC.......... National Energy Research Center (JOR)
NL .... Netherlands
NREA .... National Renewable Energy Agency (EGY)
NREL .... National Renewable Energies Laboratory (USA)
NSO .... Nevada Solar One (USA)

O&M .... Operation and Maintenance
OA.............. Operating Agent (SolarPACES)
OECD......... Organization for Economic Cooperation and Development
OGC .... Open GIS Consortium
ONE............ Office National de l'Electricite (MAR)

P.................. Portugal
PAL .... Palestine
PCM .... phase change materials
PDVSA........ Petróleos de Venezuela
PET .... polyethylene terephthalate

PIER	Public Interest Energy Research (CA-USA)
POL	Poland
PPA	power purchase agreement
PROMES	Laboratoire Procédés, Matériaux et Energie Solaire, CNRS (F)
PSA.............	Plataforma Solar de Almería (E)
PSE	Projektgesellschaft Solare Energiesysteme GmbH,
PSI	Paul Scherrer Institute (CH)
PUA	Public Utilities Authority (IL)
PVDSA	Petróleos de Venezuela, S.A.
PVGIS..........	Photovoltaic Geographical Information System
PVPS...........	Photovoltaic Power Systems Agreement (IEA)
QF	Quench flow
RCSI	Royal College of Surgeons in Ireland (IR)
RD	Royal Decree (E)
REDI............	Renewable Energy Development Initiative (AUS)
REV.............	representative elementary volume
REWP	Renewable Energy Working Party
RFP	request for proposal
RFA.............	Radiative Flux Assessment (GEWEX)
RPC	reticulate porous ceramic
RPS	Renewable Energy Portfolio Standard (Calif., USA)
S..................	Sweden
SAIC	Science Applications International Corp.
SBP	Schlaich Bergermann und Partner (D)
SDIC	Spatial Data Infrastructure Community
SEGS	Solar Electric Generating Systems
SEIA	Solar Energy Industries Association (USA)
SEPA...........	Solar Electric Power Association
SES..............	Stirling Energy Systems, Inc.
SEWPA	Solar Energy and Water Processes and Applications (Task 6)
SHC	Solar Heating and Cooling Implementing Agreement (IEA)
SHIP	Solar Heat for Industrial Processes
SOAP	Simple Object Access Protocol
SNL	Sandia National Laboratories (USA)
SODIS..........	Solar Water Disinfection
SolarPACES	Solar Power and Chemical Energy Systems
SONDA	National Network of Environmental Data for Renewable Energy Resource Assessment (BRA)
SPG	Solar Power Group
START	Solar Thermal Analysis, Review and Training
SUNY	State Univ. of New York
TCE.............	trichloroethylene
TEM	transmission electron microscope
TGA............	Thermogravimetric Analysis
TUN.............	Tunisia
UC	University of Colorado (USA)
UK...............	United Kingdom
UNDP	United Nations Development Program

UNED .... National Univ. Distance Education (E)
UNEP........... United Nations Environment Program
UNLV .... Univ. Nevada Las Vegas (USA)
USA .... United States of America
USACH .... Univ. Santiago de Chile

VOCS .... volatile organic chemicals
VR .... vacuum residue

WGA .... Western Governors Association (USA)
WH.............. Westinghouse cycle
WIS.............. Weizman Institute of Science (IL)
WMO .... World Meteorological Organization
WSDL .... Web Services Description Language

YEM .... Yemen

ZA .... Republic of South Africa
ZAE .... Zentrum für Angewandte Energieforschung e.V.
ZSW............. Zentrum für Sonnenenergie und Wasserstoff-Forschung (D)
ZWE............. Zimbabwe

Part 1: Report of the SolarPACES Executive Committee for 2007

by
Michael Geyer
IEA SolarPACES
Executive Secretary

1 Report of the SolarPACES Executive Committee for 2007

Part 1 of this Report, which gives an overview of results and achievements of the SolarPACES Implementing Agreement in 2007, is submitted to the IEA by the SolarPACES Executive Committee as stipulated in Article 3(f) of the Implementing Agreement.

Part 2 presents an update on the introduction of concentrated solar power on the international market, ongoing international projects, policies and benefits, especially in sunbelt regions, such as southern Europe, North-Africa, the southwest U.S. and broad regions of the developing world.

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 in previous years, it is also the aim of the Annual Report for the year 2007 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

IEA SolarPACES *VISION*	Make a significant contribution with concentrating solar power (CSP) technologies to the delivery of clean, sustainable energy services in the world's sun belt.
IEA SolarPACES *MISSION*	Facilitate, coordinate and maintain concentrating solar technology research, development and demonstration through international cooperation and information exchange, leading to the deployment and commercialization of sustainable, reliable, efficient and cost-competitive concentrating solar power technologies.
IEA SolarPACES *STRATEGY*	Assist the participating countries in expanding the use of economical, reliable and efficient concentrating solar technologies in a manner linked to and consistent with the REWP strategy and goals.

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.

Specific examples of expanded outreach and market development are:

- In 2002, SolarPACES joined forces with UNEP, the Global Environmental Facility (GEF) and the Solar Thermal Industry Associations of Europe and the U.S.A. to develop the Concentrated Solar Power (CSP) Global Market Initiative (GMI) to facilitate building 5,000 MW of CSP power plants worldwide over the next ten years. This initiative represents the world's largest coordinated action in history for the deployment of solar electricity.
- In 2004, the SolarPACES GMI proposal was included in the International Action Program (IAP) of the International Conference for Renewable Energies, held 1-4 June 2004, in Bonn, Germany.
- In 2007, the CSP Global Market Intiative joined forces with the EMPower project, sponsored by the Global Environment Facility (GEF) through the United Nations Environment Programme (UNEP), KfW (the German Development Bank) and the Solar Electric Power Association (SEPA) and the German Ministry for Technical Cooperation and Development (BMZ).
- Reaching out to other IEA Implementing Agreements, SolarPACES has extended its collaboration to the PVPS and SHC implementing agreements on the crosscutting issues of solar resource assessment and the application of CSP technologies for industrial processes.
- Recently, SolarPACES responded to an invitation to participate in the IEA Office for Energy Technology and R&D Gleneagles program of work for the proposed Climate Change, Clean Energy and Sustainable Development Initiative. Of the G8 Plus Five countries, five are active participants in So-

larPACES (France, Germany, the United States, Mexico, and South Africa), two countries are in the process of joining (Italy and Brazil), and two other countries have participated in the past (Great Britain and Russia).

The IEA SolarPACES Vision, Mission and Strategy are described in the IEA SolarPACES Strategic Plan. The IEA SolarPACES vision and mission statements focus on overcoming the technical, non-technical, 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 solar thermal 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 the 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 illustrate the range of the work of SolarPACES. Cooperative development and testing of key solar compo-

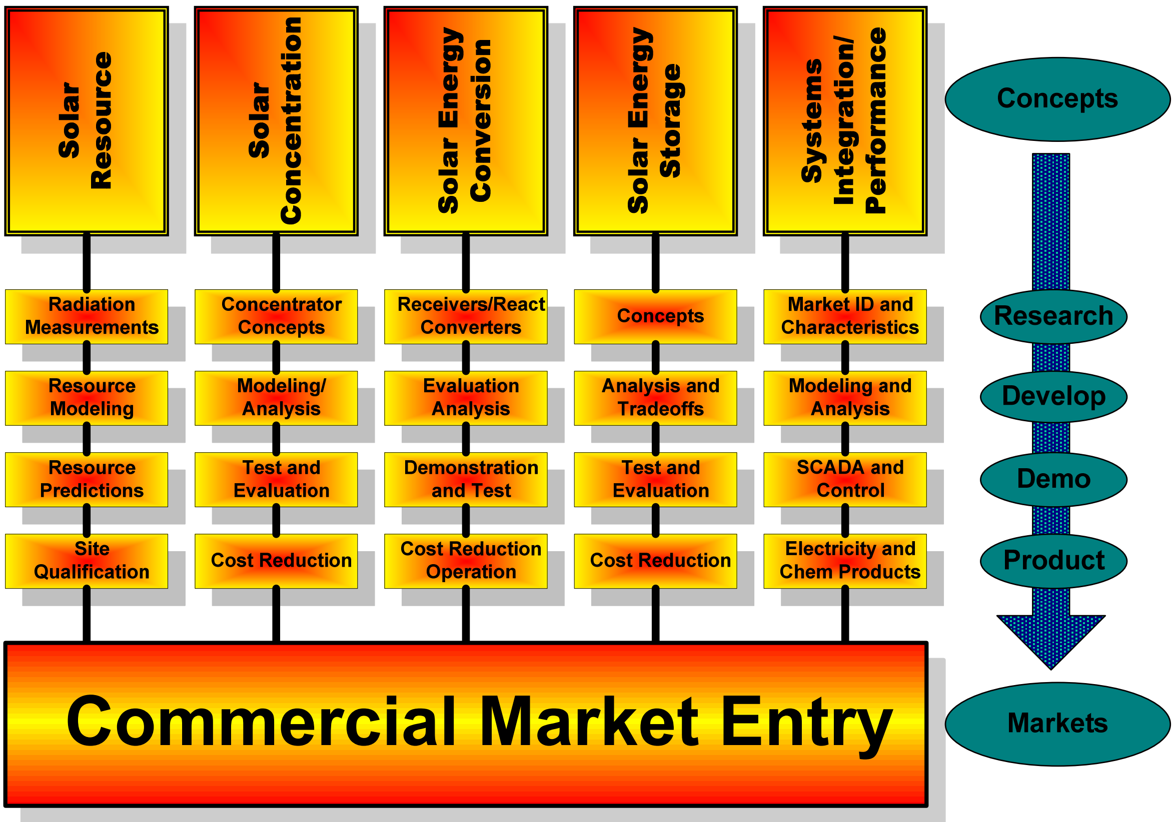


Figure 1.1. Scope of CSP research, development and demonstration work

nents, including advanced concentrators and receivers, 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, cooperative action on systems 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.

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

As of December 2007, 12 countries, or organizations designated by their governments, participate in IEA SolarPACES as shown in Table 1.1.

The SolarPACES Implementing Agreement has attracted ***non-IEA member countries***, Algeria, Egypt, Israel, Mexico, and

Table 1.1. SolarPACES Contracting Parties as of December, 2007

Country	Represented by	Govt.	R&D Institute	Industry	Electric Utility	ExCo Member
Algeria	NEAL		X			Tewfik Hasni
Australia	Consortium				X	To be nominated
Egypt	NREA	X				Samir M. Hassan
European Union	DG-RTD DG-TREN	X				Domenico Rossetti Pietro Menna
France	CNRS		X			Alain Ferriére
Germany	DLR		X			Robert Pitz-Paal
Israel	WIS		X			Michael Epstein
Mexico	IIE		X			Jorge Huacuz Villamar
South Africa	ESKOM				X	Louis van Heerden
Spain	CIEMAT		X			Diego Martínez Plaza
Switzerland	PSI		X			Pierre Renaud
United States of America	CSP Industry			X		Dale Rogers Robert Liden Gilbert Cohen

South Africa, which possess excellent solar resources for the application of solar concentrating technologies. Task Participation is shown in Table 1.2 debajo de.

Table 1.2. Task Participation

SolarPACES Task	ALG	AUS	EC	EGY	F	D	IL	MEX	RSA	E	CH	USA
I. CSP Systems	x	x	x	x	x	x	x	x	x	x		(X)
II. Solar Chemistry		x	x		x	x	x			x	(X)	x
III Technology and Advanced Applications	x	x	x		x	(X)	x	x	x	x	x	x
IV SHIP Solar Heat for Industrial Processes				x		(X)		x		x		
V Solar Resource Knowledge Management	x			x		x		x		x		(X)
VI Solar Energy And Water Processes And Applications	x			x		x	x	x		x		

Cooperation with industry is a key element in the SolarPACES activities. Over a fourth of the contracting governments designated industrial or utility partners as SolarPACES participants, e.g., Algeria (project developer), Australia (utility association), Mexico (utility), South Africa (utility) and US (industry). 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 makers, 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 biennial Symposia, about a third of the 150-200 participants come 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.

The CSP Global Market Initiative has been jointly developed with the European Solar Thermal Industry Association (ESTIA) and the Solar Energy Industry Association (SEIA) of the United States.

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. Potential for increased participation:

- Abu Dhabi, which has announced a 500-MW CSP program and is now preparing the RFP for the first 100 MW
- Algeria, which has awarded the first BOT Integrated Solar Combined Cycle in North Africa
- China, which has announced the implementation of the first 100 MW of CSP in its current five year plan
- France, which published a solar electricity feed-in tariff in 2006
- Greece, which published a CSP feed-in tariff in 2006
- Italy, which is preparing a feed-in tariff for 2008.
- Morocco, where ONE, the national utility, has awarded a combined cycle plant with integrated CSP in Ain Beni Mathar
- Portugal, where a new CSP feed-in law has been published

Other countries with high solar insolation and power demand include Jordan and Chile.

With the approval of the new IEA Framework for International Energy Technology Cooperation, which admits industrial sponsors to Implementing Agreements, further industrial participation is expected.

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

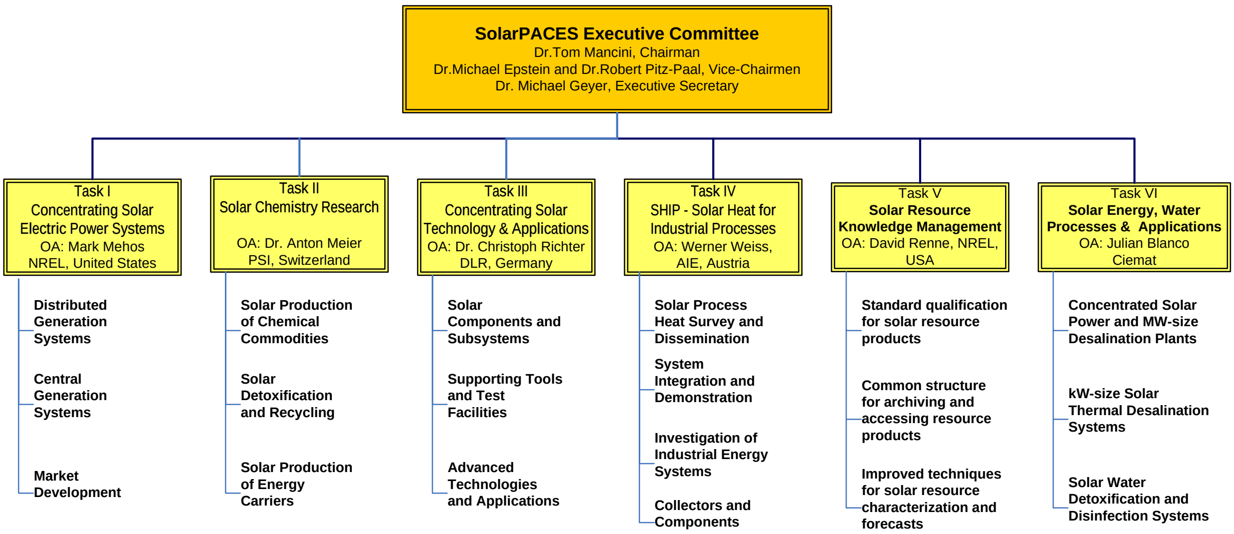


Figure 1.2. Organization of Work within the SolarPACES Task Structure

shown in Figure 1.2.

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 Task I: Concentrating Solar Power Systems

Task I addresses the design, testing, demonstration, evaluation, and application of Concentrating Solar Power (CSP) systems. It focuses on the ultimate application of complete systems and the needs associated with getting them to the marketplace. Component and research efforts of Task III will feed Task I and will help provided direction on new component needs that could be addressed through Task III. Current Task I Sectors are:

Sector I.1	Central station systems including troughs, towers, and linear Fresnel
Sector I.2	Distributed generation systems including dish/engine and other distributed systems
Sector I.3	CSP Market development addressing financial, environmental, regulatory, and marketing issues

Organization and Structure: The Task Operating Agent, currently Sandia National Laboratories, is responsible for Task organization and operation, including reporting. Activities are divided into sectors, as designated by the OA and approved by the ExCo. A Sector Leader appointed by the OA coordinates each sector. Sector Leaders are responsible for coordinating activities within their Sector.

At the 72nd ExCo Meeting in Sharm el Sheikh in May 2006, the Task I Operating Agent proposed the following reorientation of the sectors:

I.1 Communicate status of CSP projects and related data. Develop improved relational database describing commercial systems in operation, under construction, or under development.

1.2 Reduce barriers to near- and long-term deployment of CSP systems. An example is the Trough Workshop, where Stakeholders encouraged development of standards (or standard methodologies) for assessing the performance of demonstration/commercial CSP systems

1.3 Support evaluation and implementation of advanced demonstration and commercial projects

1.5 Task II: Solar Chemistry Research

Task II (Solar Chemistry Research) encompasses activities that deal with solar-driven thermochemical and photochemical processes for:

- 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 hydrogen production.
- Processing of chemical commodities: use of solar energy for processing energy-intensive, high-temperature materials.
- Detoxification and recycling of waste materials: solar energy treatment of polluted air, water, and soil, and for recycling waste 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, making use of an efficient network, for the rapid exchange of technical and scientific information. 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. Activities are classified into three sectors:

II.1 *Solar production of chemical energy carriers*: solar hydrogen, solar reforming of natural gas; solar reduction of metal oxides; solar conversion of carbonaceous materials; solar cracking of hydrocarbons; solar chemical heat pipes.

II.2 *Solar processing of chemical commodities*: solar production of metals, hydrogen, synthesis gas, carbon filaments, fullerenes, lime, cement, and other fine and bulk chemicals.

II.3 *Solar detoxification and recycling of waste materials*: solar detoxification of contaminated water, soil, and air; solar recycling of hazardous waste and of secondary raw materials.

1.6 Task III: Concentrating Solar Technology and Applications

The objectives of this task deal with the advancement of technical and economic feasibility of the emerging concentrating solar technologies and their validation with suitable tools by proper theoretical analyses and simulation codes, as well as by experiments using special arrangements and adapted facilities. For this purpose, procedures and techniques are defined design, evaluation and optimized use of the components and subsystems, which concentrate, receive, transfer, store and apply solar thermal energy. In essence, the goals are to investigate innovative multi-discipline advances needed for the further development of concentrating solar systems. This also concerns, among others, process heat applications, solar concentration for materials development, and introduction of hybrid solar/fossil power plant concepts.

Task III is an ongoing effort covering R&D-oriented activities with clearly defined technical objectives, time schedule and expected results.

For structuring purposes, each of these activities is assigned to one of the following sectors:

III.1 Solar Specific Technology Components and Subsystems
III.2 Supporting Tools and Test Facilities
III.3 Advanced Technologies and Applications

1.7 Task IV: Solar Heat for Industrial Processes

This task is an IEA Solar Heating and Cooling and IEA SolarPACES collaborative research project bringing together experts and industries from residential solar heating and high temperature solar power. Industry accounts for approximately 30% of the energy consumption in the OECD countries. The major share of the energy that is needed in trade and industry for production and heating production halls is below 250°C. To be able to make use of the huge potential for solar heat in the industry and to open a new market sector for the solar thermal industry, solar thermal systems must be suitably integrated in industrial processes. Further development of solar thermal components is especially critical to meet the requirements. Applications, systems and technologies included in the scope of this task are:

- All industrial processes requiring heat up to approx. 250°C
- Space heating of production halls or other industrial bays is addressed, but not space heating of dwellings and
- Solar thermal systems using air, water, low pressure steam or oil as a heat carrier, i.e., not limited to a any one heat transfer medium in the solar loop.

Extension of this Task beyond 31.10.2007 is not foreseen due to lack of funding, but the continuation of co-operation as an “SHC Working Group” is planned.

Activities scheduled for 2007 were a final meeting in Graz, Austria from September 10th to 12th and the finalization of deliverables:

- Set of booklets (Medium Temperature Collectors, Pilot Projects, Potential Studies, Design Guidelines – Space Heating of Factory Buildings)
- CD for Task Participants:
- PE^2 Programme (Pinch Analysis)
- Matrix of Indicators (Database for initial reference)
- GREENIUS (customized version for process heat applications)

1.8 Task V: Solar Resource Knowledge Management

The purpose of Task V is to develop and provide better information and services on solar irradiance. This concerns standardization of products, better data reliability and availability, and improved spatial and temporal coverage, with customized solar resource products, including solar radiation forecasting. Achieving these goals will reduce the cost of planning and deploying solar energy systems, improve solar system efficiency with more accurate and complete information on the solar resource, and increase the value of the solar power produced by solar systems.

Task V assembles specialists in remote sensing and meteorological modeling from seven countries. To make use of synergies the task-sharing activities in this branch are organized as a Collaborative Task together with the IEA Solar Heating and Cooling Program (SHC) and IEA Photovoltaic Power Systems. Collaboration with SolarPACES requires special emphasis on direct irradiance. This radiation component is essential for concentrating solar devices, but harder to derive and is more spatially and temporally variable.

Organization and Structure: The Task on Solar Resources is coordinated by the SHC Operating Agent Dave Renné of NREL, USA. In SolarPACES the Task is represented by Richard Meyer of DLR, Germany. Activities are structured in three sectors:

- *V.1* *Standardization and benchmarking* of solar resource products (Lead country: Germany)
- *V.2* *Common structure for archiving and accessing* resource products (Lead country: France)
- *V.3* *Improved techniques for solar resource characterization* and forecasting (Lead country: Germany).

1.9 Task VI: Solar Energy And Water Processes And Applications

This new task, proposed by CIEMAT, was established at the 72nd SolarPACES Exco Meeting in Sharm el Sheikh at the. The IEA-Solar PACES Task "Solar Energy and Water Processes and Applications" shall provide the solar energy industry, the water sector 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.

The need for development of this specific area of solar energy arises from the serious water problems expected in many areas of the world during the coming decades. With the added prospects of increasing energy costs, it makes good sense to seriously consider the use of solar energy to solve or palliate water problems. Specific technological development will be required for this.

The purpose of this Task is to improve the conditions for solar water treatment market introduction and solve water problems at locations with abundant solar energy resources, while contributing to reduced fossil-fuel consumption. The main specific focus of the activities and initiatives addressed is to show the potential of solar energy for water applications. The specific objectives of the Task are to:

- Compile existing knowledge and experience, and publicize it in SolarPACES member countries
- Provide added value to related research and development activities underway in member countries by integrating such activities into a wider support structure
- Promote specific collaborative technical and economic feasibility studies of associated technologies
- Identify potential case studies demonstrating the technical and economic feasibility of technological solutions proposed for particular locations and problems
- Attract interested companies to make knowledge transfer and suitable demonstration applications possible, analyzing the necessary ways and means for carrying out such initiatives

Task VI is structured in the following subtasks:

Sector VI.1	Concentrated Solar Power and MW-size Desalination Plants
Sector VI.2	kW-size Solar Thermal Desalination Systems
Sector VI.3	Solar Water Detoxification and Disinfection systems

1.10 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 40-50 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—ESTIA (European Solar Thermal Industry Association) and SEIA (Solar Energy Industry Association of the USA). SolarPACES is cooperating closely with these associations and has regularly invited their representatives to its ExCo Meetings.

SolarPACES joined forces with ESTIA and Greenpeace, to develop a market deployment scenario for CSP 2002-2025, which shows that nearly 40 GW of CSP plants may generate some 100 TWh of clean solar power annually by 2025.

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 INDITEP, DISTOR, EuroTrough, EuroDish, SolAir, SolGate, SOLASYS, SOLREF, SOLZINC, AndaSol, PS10 and SolarTres. The information on these projects has been shared with the non-European SolarPACES partners.

SolarPACES also gave special support to the World Bank Solar Initiative with in-kind contributions by the contracting member institutions to project identification studies in Brazil, Egypt, and Mexico, and to the World Bank's Cost Reduction Study.

Proactive cooperation with the IEA Renewable Energy Unit has continued together with other renewable implementing agreements, by participating in the Exhibition at the IEA Ministerial Meeting in April 2002, contributing to the Renewable Energy Working Party, preparing an exhibit for the Renewables 2004 Conference in Bonn, developing the IEA RD&D priorities and participating in the REWP seminars.

Proactive cooperation has been established with the Solar Heating and Cooling (SHC) Implementing Agreement with the new joint task on "Solar Heat for Industrial Processes" (SHIP) and another on "Solar Resource Knowledge Management" with the SHC and PVPS Implementing Agreements.

1.11 Information Dissemination

The key SolarPACES event for information dissemination is the biennial 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.

Some 230 participants from 24 countries gathered at the 11th SolarPACES International Symposium on Concentrated Solar Power and Chemical Systems, held September 4-6, 2002, in Zurich. The highlight was the Keynote presentation by Nobel laureate Prof. Carlo Rubbia. The Symposium Proceedings included 92 peer-reviewed papers. About a third of the 150-200 participants came from industry and utilities.

Some 200 participants from 20 countries met at the 12th SolarPACES International Symposium on Concentrated Solar Power and Chemical Systems, held October 6-8, 2004 in Oaxaca, Mexico. The 12th SolarPACES Symposium was cosponsored by Mexico's Energy Secretariat, Secretariat of the Environment and

Figure 1.3. Participants of the 72nd SolarPACES Executive Committee Meeting hold on May 9 -10th 2007 in Sharm el Sheikh, Egypt

Natural Resources, the Instituto de Investigaciones Eléctricas (MEX), the State Government of Oaxaca (MEX) and SolarPACES.

The over 500 participants from 30 countries who attended the 13th SolarPACES International Symposium on Concentrated Solar Power held from June 20-23, 2006, in Seville, Spain, had the opportunity to visit the first commercial power tower, the 10-MW PS10 plant located near Seville, and the construction site of the 50-MW AndaSol-1 plant, the first commercial parabolic-trough plant with multi-hour storage, near Granada.

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 2006*** was published and distributed to 500-1000 interested experts worldwide, giving detailed literature references and contact addresses to encourage further cooperation.

Figure 1.4. SolarPACES Home Page www.solarpaces.org

A ***SolarPACES website*** at **www.solarpaces.org** has been implemented to provide information on the internet. It has had over 300,000 visitors since January 1, 2002.

1.12 Scale of Activities in 2007

The calendar of SolarPACES-related activities in 2007 was as follows:

February

20th – 21st Participation in the IEA NEET Meeting in Johannesburg, South Africa

March

7th – 8th Organization of the Trough Workshop with NREL at Denver, Colorado

12th – 14th 3rd Task V Experts Meeting at the EC Joint Research Center, Ispra, Italy.

13th Joint CSP Workshop with BP in Almeria

15th	Participation in the IEA REWP meeting in Paris, France
19th – 21st	Participation in the EMPower Utility Findings Workshop hosted by KfW in Berlin, Germany
28th – 30th	Task IV Experts Meeting in Cologne, Germany

April

19th	Participation in the SET Workshop of the European Commission in Brussels, Belgium

May

7th – 8th	Participation in the ADST2007 Third International Conference and Exhibition Desalination Technologies And Water Reuse in Sharm el Sheikh, Egyptç
9th – 10th	72nd SolarPACES Executive Committee Meeting, hosted by NREA in Sharm el Sheikh, Egypt
11th	Host Country Day, hosted by NREA in Sharm el Sheikh, Egypt
31st	Participation in the DERBI workshop in Perpignan, France

June

18th-19th	Participation in the CEER Conference in Algiers, Algeria
21st	Participation in the Menarec4 Conference
18th – 22nd	Organisation of visit of US DOE Delegation to CSP projects in Spain
27-30th	Participation in the ASME Energy Sustainability Conference, Long Beach, CA, USA,

July

September

19th – 21st	Participation in ISES International Conference in Beijing, China
19th	Task III Meeting during the ISES International Solar Energy Conference in Beijing, China
27th	Participation in DISTOR Workshop at PSA

October

23rd – 25th	4th Task V Experts Meeting hosted by SunTechnics GmbH in Hamburg, Germany, followed by a user workshop.
30th	Participation in Swiss Workshop on Concentrated Solar Power (CSP) – Research orientations in Switzerland, hosted by PLANAIR in Neuchatel, Switzerland

November

13th	Task VI kickoff meeting in Paris, in conjunction with the 73rd SolarPACES ExCo meeting.
14th – 15th	73rd SolarPACES ExCo Meeting hosted by CNRS in Paris, France

December

13th	Participation in the Energy Science Kolloquium at the ETH in Zurich, Switzerland

Part 2:
INTRODUCING CONCENTRATED SOLAR POWER ON THE INTERNATIONAL MARKET – POLICIES AND BENEFITS

Michael Geyer, Executive Secretary

2 INTRODUCING CONCENTRATED SOLAR POWER ON THE INTERNATIONAL MARKET – POLICIES AND BENEFITS

Dr. Michael Geyer, Executive Secretary SolarPACES

2.1 Introduction

Concentrating solar power (CSP) is the lowest-cost and the largest bulk producer of solar electricity. CSP (also referred to as solar thermal power) can meet a significant percentage of the future global electricity demand without technical, economic or resource limitations, especially in Sunbelt regions, such as the southwest U.S., southern Europe and wide areas in the developing world, where one square kilometer of land would be enough to generate as much as 100-200 GWh of electricity per year. This is equivalent to the annual production of a 50-MW conventional coal or gas-fired power plant. Massive CO_2 reduction from worldwide exploitation of less than 1% of the total solar thermal potential would be enough to stabilize global climate.

Solar thermal power plants can be designed for solar-only generation, to satisfy a peak load demand, but ideally, with storage systems, up to a 100% solar share could be achieved in the future. This potential and their ability to dispatch power on demand during peak periods are key characteristics that have motivated regulators in the Mediterranean Region, starting with Spain, to support large-scale implementation of this technology with tailored feed-in tariffs.

CSP systems have been in use since the early eighties to generate electricity and heat. The US$1.2-billion investment in nine commercial parabolic-trough solar power plants (known as the SEGS plants) totaling 354 MW_e, in California's Mojave Desert between 1984 and 1991 and their successful operation and performance, demonstrate the readiness of CSP. By 2007, these California plants, still operating reliably, have produced more than 50% of all solar electricity. After a long interruption imposed by low electricity prices, the solar experience was taken up again in June 2007 when the Nevada Solar One 64-MW parabolic-trough plant, financed by a long-term power purchase agreement, was connected to the grid. In late 2002, Spain passed a solar thermal power feed-in premium law, which has triggered the development of over 1000 MW of new CSP plant projects. The first of those, the 11-MW PS10 solar tower plant, was connected to the grid in early 2007. Construction of the first 50-MW parabolic-trough plants, Andasol and SolNova, began in southern Spain in 2007 and will be connected in 2008. In North Africa, Algeria became the first country to introduce a feed-in law for hybrid solar gas integrated combined cycles in 2004. Construction began in 2007 on a 135-MW-capacity combined cycle power plant with a 30-MW solar field. With Global Environmental Facility funding, a large 300-MW-capacity integrated solar combined cycle plant, also with a 30-MW solar field, was contracted in Morocco in mid 2007.

Electricity from solar thermal power is also becoming more and more economical. Plants operating in California have already achieved impressive cost reductions, with generating costs of 18 to 35 US cents/kWh, depending on the solar resource available, plant type and size, and forecasts are for less than 15 US cents. Advanced technologies, mass production, economies of scale and improved operation will all contribute to cost reduction, making solar electricity competitive with other power resources within the next 10 to 15 years. The CSP industry expects solar electricity generation to be fully competitive with fossil-based, grid-connected power starting from a global 5,000 MW_e installed of CSP solar capacity.

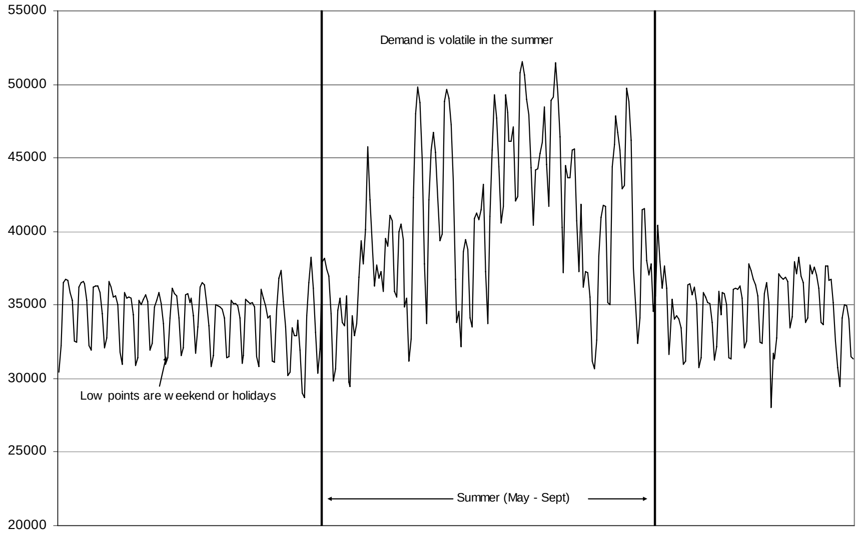
2.2 Benefits for the power markets

Skyrocketing use of air conditioners and other cooling devices are making the worldwide summer peak power demand stronger than in winter. Figure 2.1 shows the typical annual power load curve for California, in which the summer peak load capacity is almost 50 GW, nearly doubling base-load capacity.

Figure 2.2 shows the growing monthly electricity demand in mainland Spain, with clear growth of summer demand.

CSP plants are fueled by the same power source that causes the summer air-conditioning peaks – the sun. Their output is therefore perfectly synchronized with demand. While base-load electric power is provided by coal–fired, nuclear and some hydroelectric plants operating around 7000-8000 hours a year, conventional peak power is increasingly being met by gas turbines operating only 500 to 2000 hours per year to produce the most expensive conventional electricity. Near-term CSP plants will replace such peaker gas turbine power plants, and in the midterm, with increasing storage capacity, will be able to replace mid-load power plants.

CSP is suitable for large-scale 10 to 200 MW_e plants, replacing conventional thermal power capacity. With thermal storage or fossil backup, CSP plants can also produce power when radiation is low and at night. Solar thermal power plants can reliably deliver firm, scheduled power while the grid remains stable. So-



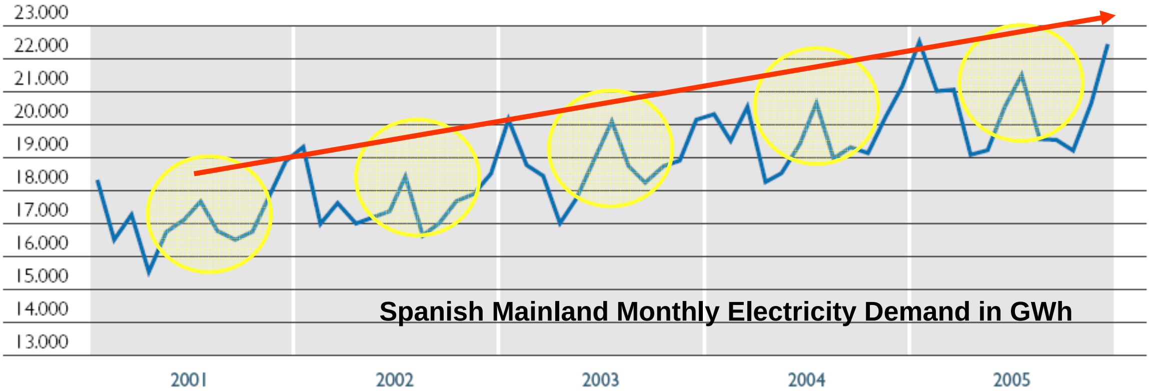
(Source: California Energy Commission)

Figure 2.1. Typical Annual Power Load Curve in California

lar thermal power generation can be combined with conventional thermal power plants, leading to substantial cost reduction and facilitating market entry of renewable energies, particularly in threshold countries.

Solar energy has enormous potential in Sunbelt power markets as a fossil-fuel supplement or alternative fuel. In the near term, solar energy can reduce the utility natural gas demand, allowing natural gas to be used for higher-value applications, including peak power, while diversifying their fuel portfolio.

CSP life-cycle assessments, including emissions and land-use, show that it reduces greenhouse gas emissions and other pollution with no environmental risks of its own. Each square meter of CSP concentrator surface is enough to avoid the annual production of 250 to 400 kilos of carbon dioxide. The energy payback time of concentrating solar power systems is on the order of just five months. This compares very favorably with their lifespan of approximately 25 to 30 years. Most of the CSP solar field materials can be recycled and reused in new plants.



(Source REE)

Figure 2.2. Growth of the monthly electricity demand in mainland Spain 2001-2005

2.3 Integration of Concentrating Solar Power in Commercial Power Plants

State-of-the-art commercial CSP technology is defined by the nine parabolic-trough SEGS plants with 354-MW total capacity built in California's Mojave Desert in the early 80s, the recently inaugurated CSP projects and those now under construction in Spain and the US.

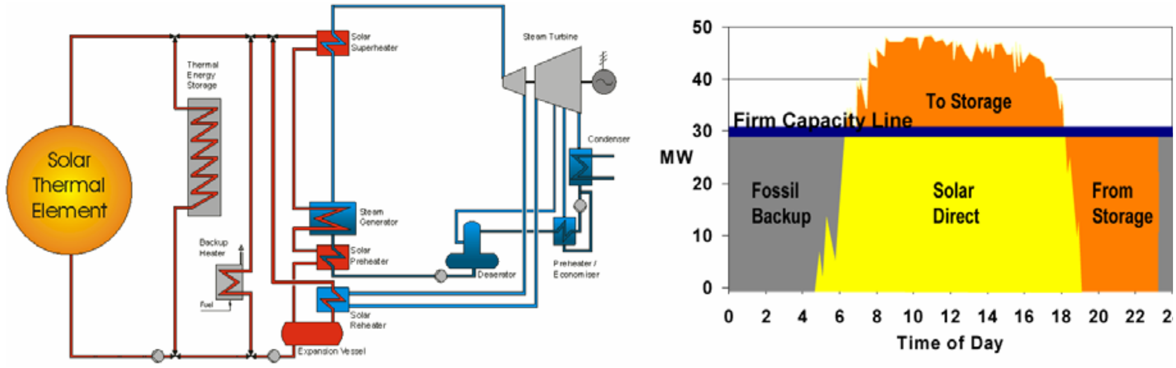


Figure 2.3. CSP power generation in steam cycles

All commercial CSP plants, whether solar power towers with water/steam, molten salt, sodium or open air receivers, or parabolic troughs or Fresnel collectors with a heat transfer fluid or direct steam generation, generate solar steam for a turbine in a Rankine Cycle or Combined Cycle plant, whether with high solar shares or solar-only operation and with correspondingly large amounts of cooling water.

Fossil backup and/or storage may be used to extend operation beyond the hours of sunlight and provide firm, dispatchable power. In the first-generation SEGS plants in California, 25 percent of annual power generation was allowed to be generated by gas. The Nevada Solar One plant is only allowed to use gas for freeze protection, but not for power production. The feed-in law in Spain allows use of up to 15% gas for power production during the year. The reason for this limitation is the relatively low cycle efficiencies of solar steam plants, which are at best about 37% annual conversion efficiency, while in modern combined-cycles, gas can be burnt with over 50% efficiency.

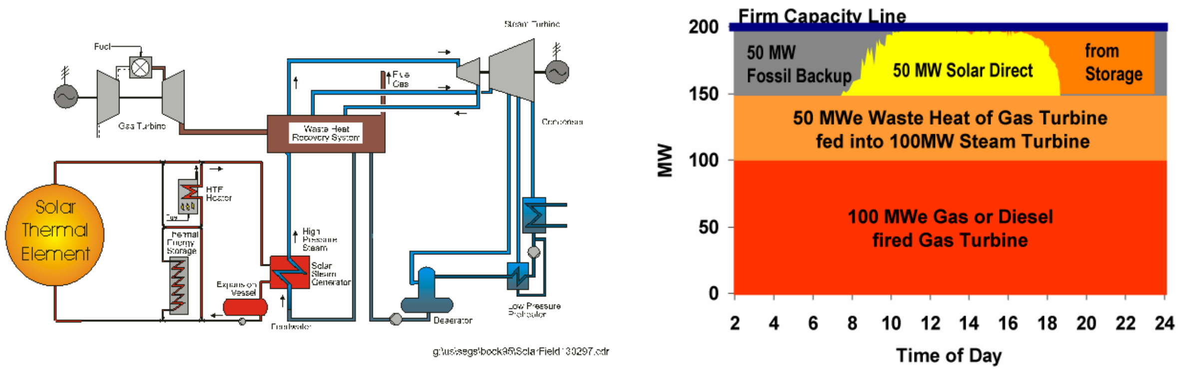


Figure 2.4. CSP power generation in Integrated Solar Combined Cycles (ISCC)

Solar thermal plants may be combined with a high fossil share in fuel-efficient Integrated Solar Combined Cycle (ISCC) systems. In ISCCS power plants, a solar parabolic-trough field is integrated in a modern gas and steam power plant, where the waste heat boiler is modified and the steam turbine is oversized to provide additional steam from a solar steam generator. Better fuel efficiency and extended operating hours make combined solar/fossil power generation much more cost-effective than in separate CSP and combined cycle plants. Without storage, however, solar steam could only be supplied for some 2000 of the 6000-8000 combined cycle operating hours, and since the solar steam is only feeding the combined-cycle turbine, which supplies only a third of its power, the solar share obtainable is under 10%. This is of especial interest for oil and gas-producing Sunbelt countries, where solar power technologies can be introduced on their fossil-based power market. Such is the case of Algeria, where a special ISCC feed-in tariff has been passed. For this reason, the Global Environmental Facility (GEF) is provide US$200 million in subsidies exclusively for gas and steam/solar hybrid power projects. The first has now been contracted in Morocco and the second is under final negotiation in Egypt.

2.4 Economic Feasibility and Financing Requirements

CSP plant cost structure is constrained by its high initial investment. Over the entire life cycle of the plant, 80% of the cost is from construction and associated debt, and only 20% is from operation. Therefore financial institution confidence in the new technology is critical. Only when they make funds available without high-risk surcharges can solar thermal power plant technology become competitive with medium-load fossil-fuel power plants. Once the plant has been paid for, in 25 or 30 years, only operating costs, which are currently about 3 cents/kWh, remain, and the electricity is cheaper than any competition, comparable only to long-written-off hydropower plants.

Commercial experience from the nine SEGS plants, built by Luz International, Ltd. from 1986 through 1992 and operating continuously since, shows that power generation costs (in 2004 US$) dropped in only seven years from \$0.44/kWh$_e$ for the first 14 MW$_e$ unit to just \$0.17/kWh$_e$ for the last 80 MW$_e$ unit. (As a reference, in 1985 US dollars, the cost of electricity from the first 14 MW$_e$ unit was \$0.25/kWh$_e$.) With technology improvements, scale-up of individual plant MW capacity, increasing deployment rates, competitive pressures, thermal storage, new heat transfer fluids, and improved operation and maintenance, the future cost of CSP-generated electricity is expected to drop even further.

These factors were considered in two recent independent comprehensive evaluations of CSP trough and power tower technologies requested by the World Bank and the US Department of Energy. Both studies found future potential for direct competition with fossil power.

Many factors affect the cost of CSP electricity, especially the solar resource, but grid connection and local infrastructure, project development, the rate of technology advancement and mass production also affect the cost. While scaling-up plant size is the best way to reduce the cost of power, a number of technology R&D advances have been identified that can also significantly lower costs. These include increasing collector size, improving receiver efficiency and developing advanced thermal storage technologies and heat transfer fluids. Finally, increased market competition, solar field component and subsystem production volumes all enter into play in lowering the cost of CSP-generated electricity. The financial cost of power can also be reduced through preferential financing conditions and tax or investment incentives.

Because of the 15-year break between construction of the last SEGS IX plant in 1992 and PS10 and Nevada Solar One grid connection in 2007 the new industry players have had to recalculate costs and risks for a new series of CSP plants from the beginning. Engineering, Procurement and Construction (EPC) of a turnkey plant like the 50 MW Andasol-1 with a 510,120-m^2 collector field and a 7.5-hour molten-salt storage system amounts to 5200 Euro/kW. To this, the cost to of land, permits, grid connection, project development and financing must be added. This should not be compared, however, with the EPC cost of photovoltaic plants, since a CSP plant with storage like Andasol will generate some 3520 equivalent full-load hours per year, based on direct normal irradiation (DNI) of around 2100 kWh/m^2 year.

CSP operating costs have now entered a phase of constant optimization, dropping from 8 cents/kWh to just over 3 cents/kWh. Experience has provided the basis for a new generation of improved-performance parabolic-trough components. Due to its inexhaustible energy potential, technical performance, and environmental friendliness, solar thermal power plant technology is now in a position to make an essential contribution to future worldwide power supply.

In addition to the investment, financing and operating costs, the levelized electricity cost of CSP plants depends largely on the available solar resource. For like plants under the same price and financing conditions, in the Southwestern United States or Upper Egypt, where the DNI is from 2600-2800 kWh/m^2yr, the levelized electricity cost will be 20-30% lower than in Southern Spain or the North African coast where the DNI is from 2000-2100 kWhh/m^2yr. In France, Italy and Portugal, the solar resource only offers a DNI of 1700-1900kWh/m^2yr. The best solar resource in the world is in the deserts of South Africa and Chile, where almost 3000 kWh/m^2yr have been measured.

The economic feasibility of a project is therefore first determined by the suitability of the available solar resource at the site and then by power sale conditions. If the local power purchase price does not cover the production cost, then subsidies or soft loans may cover the incremental cost gap to the available tariff. Carbon credits may be an additional source of income.

All the CSP Plants in the United States, from SEGS I to Nevada Solar One, pre-financed by developers and/or suppliers/builders, received non-recourse project financing only after successful startup. In contrast, all CSP projects in Spain, from the

11-MW PS10 to the 50-MW Andasol plants, received non-recourse project financing for construction. Extensive due diligence preceded financial closure and only prime EPC contractors were acceptable to the banks, which required long-term performance guarantees accompanied by high failure penalties.

Bankability of the revenue scheme – be it a long-term power purchase agreement or a feed-in tariff, have been the key to project finance in Algeria, Spain and the US. It took considerable effort during the long years of project development to remove the barriers and obstacles to bankability:

In Algeria, the major obstacle to bankability of the feed-in tariff was the credit rating of the legal off-taker, in this case the national electric utility. Private developer negotiation for financial closure of the first Algerian ISCC plant included replacing the national electric utility by the national oil company, since it had a more satisfactory credit rating.

In Spain, the major barrier to the first feed-in tariff passed was the right of the government to change tariffs every year, which gave no long-term business plan income security. This barrier was removed by the publication of a new version of the feed-in law which now grants the solar power tariffs for 25 years.

In the U.S., the major obstacle to bankability was also the low credit rating of the off-taker, the state electric utility in Nevada. In this case, the problem was solved by a legal ruling granting continued payment of the electricity price even in case of bankruptcy of the electric utility.

2.5 Worldwide Project Development in 2007

Despite the success of the nine SEGS plants operating in California, the steady fall in energy prices during the 1980s and a delay in renewal of California's solar tax credits, led to the collapse of the project's promoter, Luz International, and no new commercial plants were built from 1991 to 2006. Progress in marketing was further hampered by the worldwide liberalization of the electricity sector. This significantly affected the feasibility of large, capital-intensive generating plants. Lack of firm market prices and long-term power purchase agreements has increased uncertainty and lowered the depreciation time for capital investments. The result has been a shift towards low capital-cost plants like combined-cycle gas firing, with short construction periods, installed costs falling to below $500/kW and generation efficiencies of over 50%. In this climate, solar thermal plants still need to scale up to larger unit capacities in order to compete successfully for the generation of bulk electricity.

Counterbalancing this trend is a growing concern for global warming and pressure from international agreements, often translated into national targets and support mechanisms, for the accelerated development of environmentally-friendly, nonpolluting power systems, which produce little or no carbon dioxide emissions. But although 'green power markets' have been advancing in both Europe and North America, with premiums paid by customers or state funds for electricity generated from renewable resources, solar thermal power has generally not been included in the list of qualifying technologies.

However, global concern for clean energy solutions is providing a new perspective. Some of the main investors in the developing world, including the World Bank's Global Environment Facility (GEF), the German Kreditanstalt für Wiederaufbau (KfW) and the European Investment Bank (EIB), have shown their confidence in the environmental promise and economic prospects of solar thermal power. The European Union's 5th, 6th and 7th Framework Programs have also funded demonstration and marketing projects, with particular interest in the northern Mediterranean Sunbelt, and national RD&D programs in Germany, Israel, Italy, Spain and the United States.

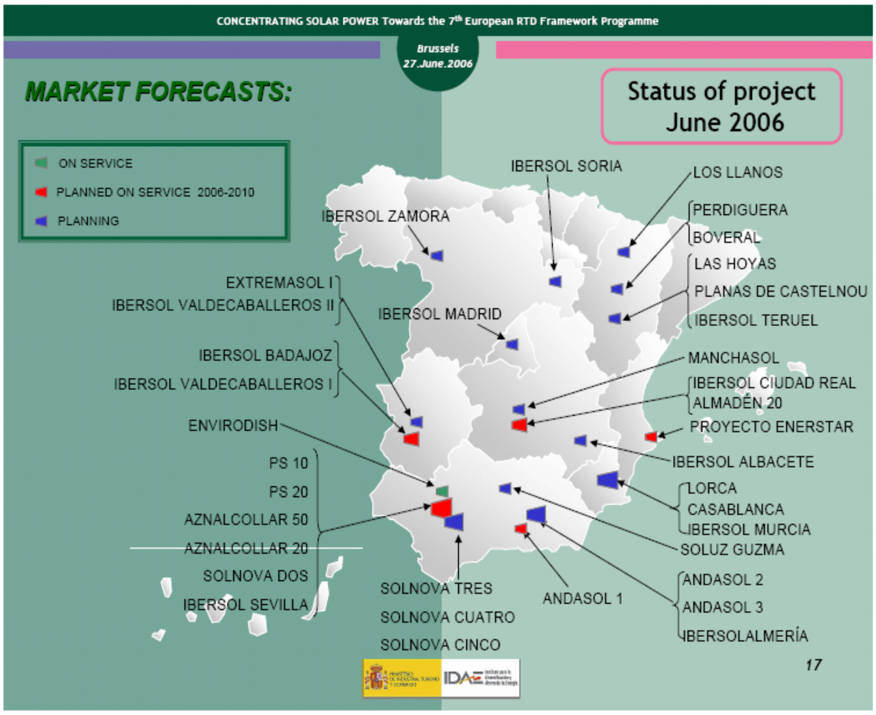
Such RD&D funding has not only helped sustain the technology, but achieve significant advances leading to market revival, however, alone they could not have reawakened the market.

The European Parliament and the Council on the promotion of the electricity produced from renewable energy sources in the international electricity market passed "COM 2001/77/EC: Directive on Electricity Production from Renewable Energy Sources and of the Council on the Promotion of Electricity Produced from Renewable Energy Sources in the Internal Electricity Market" The dual purpose of this Directive was to promote an increased contribution of renewable energy sources to electricity production in internal electricity markets and to create a basis for a future Community framework. It required European member states to implement incentives for market introduction of renewable power in order meet Europe's Kyoto commitment. Among the various instruments implemented by the different member states, the renewable feed-in tariffs chosen by Spain and Germany have demonstrated by far the greatest success in implanting renewable electricity generation. Worldwide project development and market opportunities are summarized below.

Spain

In September 2002, Spain was the first European country to introduce a "feed-in tariff" funding system for solar thermal power, which granted a 12€-cent-per-kWh output premium to 100-kW to 50-MW-capacity solar thermal plants, modifiable every four years. But this was not bankable and did not cover first-project costs or risks. The solar thermal premium was therefore increased in March 2004 with the publication of Royal Decree (RD) 436, which raised the solar thermal feed-in premium 50% from 12 to 18€ cents/kWh making solar thermal power projects feasible, and reminding of California's Standard Offers in the late eighties, by:

- Granting a premium of 0.18 Euro/kWh on top of the electricity pool price or a fixed tariff of 0.21 Euro/kWh for PV and solar thermal plants of from 100 kW to 50 MW
- Making it bankable with a 25-year guarantee
- Adapting annually to the price of electricity
- Allowing 12-15% natural gas backup to provide dispatchability and firm capacity



(Source: IDAE)

Figure 2.5. Status of CSP Project Development in Spain as of June 2006

The above feed-in tariff legislation was recently further defined by Royal Decree 661 of 2007. A basic change from RD436 is its detachment from the market reference price, which increased with oil price, automatically increasing renewable tariffs. A fixed tariff of 0.269375 Euro/kWh is now granted for CSP plants up to 50 MW for 25 years, increasing yearly with inflation minus 1 percent point, and the 2010 CSP target was increased to 500 MW.

Since this tariff may be revised after implementation of the first 500 MW, a race has started in Spain to be among the first, and ongoing CSP project developments in Spain can hardly be counted. Figure 2.5 shows a snapshot of ongoing CSP project developments as of June 2006 by the Spanish Institute for Energy Diversification and Saving (IDAE).

The first Spanish CSP project to connect to the grid is the Abengoa Group's 11-MW PS10 solar power tower near Seville (Figure 2.6). The PS-10 project received €5 million from the European Union 5th Framework program. It has a 74,880-m^2 heliostat field of 624 120-m^2 heliostats, a saturated-steam receiver and a 30-minute storage system. It will generate 24 GWh of solar electricity annually.

Construction has already started on Abengoa's second power tower, the 20-MW PS20, which will be connected in 2008 at the same site. Abengoa's Plataforma Solar de Sanlucar la Mayor (PSSM) will be the world's largest solar platform, with a total CSP capacity of 300 MW, including the 10-MW PS10, two 20-MW PS20 power towers and five 50-MW SolNova parabolic-trough plants. At the same time, PSSM will become the group's CSP R&D test center.

(Source: Solucar)

Figure 2.6. View of Abengoa's Plataforma Solar de Sanlucar la Mayor showing the 11-MW PS10 and the 20-MW PS20 under construction near Seville, Spain

Figure 2.7 shows the AndaSol-1 construction site in the Marquesado Valley near Granada, where the ACS Group, SENER and the Solar Millennium Group are promoting three 50-MW parabolic-trough plants with 7.5 hours of storage. The AndaSol-1 project received a €5-million grant from the European Union 5th Framework Program and project financing from the European Investment Bank. It has a 510,120-m^2 parabolic-trough solar field and a 7.5-hour molten-salt storage system and will generate 176 GWh annually.

(Source: ACS Cobra)

Figure 2.7. View of the 50-MW AndaSol-1, promoted by ACS Cobra, SENER and Solar Millennium in the province of Granada, Spain, under construction

The United States

Nevada Solar One (NSO) groundbreaking took place at the Boulder City, Nevada, construction site on February 11, 2006. Construction of the 64-MW parabolic-trough plant started immediately afterwards and was completed in May 2007 (Figure 2.8). Commercial operation of NSO, which began in June 2007, will produce more than 130 GWh annually. Under development by Solargenix Energy since 2003, it is owned jointly by Solargenix and Acciona Energia, which purchased 55% of Solargenix Energy, forming the new Acciona Solar Power.

Several more paths towards CSP market development have gained momentum over the last year, all focused on projects in the US Southwest, encouraged by both the excellent direct-beam solar resource and demand for power from a growing population. In 2002, the US Congress asked the Department of Energy (DOE) to develop and scope a policy initiative for reaching the goal of 1,000 MW of new parabolic-trough, power-tower and dish/engine solar capacity to supply the Southwestern United States by 2006. Since late 2006, electric utility companies in the Southwest have launched several thousand MW of renewable request for proposals (RFPs), including CSP.

(Source: Acciona Solar Power)

Figure 2.8. View of the 64-MW Nevada Solar One plant at Boulder City, Nevada

The Western Governors' Association (WGA) Clean and Diversified Energy Advisory Committee's Task Forces on Advanced Coal, Biomass, Energy Efficiency, Geothermal, Solar, Transmission and Wind have identified the necessary changes in state and federal policy to achieve 30,000 MW of new clean, diversified energy generation by 2015, a 20% increase in energy efficiency by 2020 and adequate transmission capacity for the region over the next 25 years. In the 2006 WGA Report, the Solar Task Force identifies 4000 MW of high-quality CSP sites in the American Southwest US and recommends a process for developing state policies and deployment incentives.

In 2003, Nevada passed a Renewable Energy Portfolio Standard, which requires the State's two investor-owned utilities (Nevada Power, Sierra Pacific Power) to generate at least 15% of their retail electricity sales from renewable energy by 2013. The State of California's Renewable Energy Portfolio Standard (RPS) will require investor-owned utilities to produce 20% of their retail electricity sales from renewables by 2017. Out-of-state generators are subject if they deliver electricity directly into California. The state of New Mexico has had a Renewable Portfolio Standard in place since July 2003, which already required investor-owned utilities to generate at least 5% of their retail power sales from renewables for New Mexico customers by 2006, and at least 10% by 2011. The Arizona Environmental Portfolio Standard (EPS) will increase to 1.1 percent in 2007 (60% from solar sources); these requirements may be met with out-of-state solar energy if it is proven that it reaches customers in Arizona. The State also has renewable energy credit multipliers, which provide additional incentives for in-state solar power generation.

Algeria

Algeria has taken on its own domestic commitment to increase the solar percentage in its energy mix to 5% by 2010. But beyond this, Algeria would like to see a close partnership with the European Union in which Algerian plants deliver green energy needed for Europe to meet its targets. In view of this policy, New Energy Algeria (NEAL) was created to enhance participation of the local and international private sectors. On March 28, 2004, the Algerian Government published "Decret Executif 04-92" on diversification of the cost of electricity production in the Official Journal of Algeria No. 19 to promote the production of solar electricity in integrated solar combined cycles. This decree sets total ISCCS electricity production premiums, depending on the solar share, from 100% for a 5-10% solar share up to 200% for a solar share over 20%.

In June 2005, NEAL issued a request for BOT bids to national and international investors for building, financing, operation and maintenance, and transfer of a 150-MW hybrid solar/gas power plant in Hassi-R'mel, Wilaya de Laghouat, marketing electricity produced according to the provisions of Decree n° 04-92. NEAL will hold 34%, the investors 66%. The total project price is around 316 million Euros, of which 256 million correspond to the EPC contract. Construction time is 33 months. Minimum guaranteed annual production is 1,276 GWh/year. The RFP requested a tariff under 6 cents/kWh, with a solar share of over 5% and an IRR in the range of 10 to 16%. The Abengoa group won the contract and reached financial closure with NEAL in early 2007.

Morocco

A first prospective evaluation for solar thermal plants in Morocco was provided by a 1992 EU-funded pre-feasibility study. In 1999, the Global Environmental Fund (GEF) awarded the national electric utility, ONE, a US$700 000 grant to prepare the technical specifications of a 228-MW_e Integrated Solar Combined Cycle System with a 30-MW_e solar field of about 200,000-m^2, the bid documents and evaluation of offers. A GEF grant of US$50 million will cover the incremental cost of the solar component. In May 2002, two invitations for expression of interest were issued for implementation as an Independent Power Project, but in view of the lack of response, the project is being carried out as a turn-key power plant construction, and five-year operation and maintenance contract. In April 2004, a General Procurement Notice was published. This time industry response was high, leading to the prequalification of four international consortia. In February 2005, the bid documents were submitted to the World Bank for “Non-Objection”. Financing will be by the African Development Bank. The contract went to Abengoa subsidiary Abener, giving the Spanish company the go-ahead to build the 470-MW station at Beni Mathar in the north-east. The station is to begin operation early in 2009.

Egypt

Two 1995 pre-feasibility studies on parabolic-trough and central tower technologies, followed by a SolarPACES START mission in 1996 led to the decision to implement a first 150-MW Integrated Solar Combined Cycle system with a 30-MW parabolic-trough solar field. The GEF provided consultancy services and offered to cover the incremental cost. The conceptual design and project concept were prepared in 1998. In 2000, the first phase detailed feasibility report was completed, followed by a short list of qualified and interested developers in 2001. Due to the unexpectedly high US Dollar-Egyptian Pound exchange rate, new independent power project financing was required to be in local currency or in foreign currency on the condition that annual repayments should be from export revenues achieved by the project. In May 2003, a World Bank found no international developer or investor interest in the new framework, so in June 2003, it was decided to make it a governmental project allowing private sector participation in a 5-year O&M contract.

A general Procurement Notice was published in February 2004. 35 firms expressed their interest. The new prequalification and bid documents were prepared in 2004. The thermal plant will be co-financed by a JBIC soft loan for US$97-million. The project will be owned by NREA which will cover the local currency required for the project. In September 2007, NREA contracted a consortium of IBERDROLA and Mitsui to build the Combined Cycle Power Island and a consortium of Orascum and Flagsol to build the solar field.

Israel

In 2002, the Israeli Ministry of National Infrastructures, which is responsible for the energy sector, made CSP a strategic component of the electricity market. Power units are a minimum of 100 MW_e with an option for increasing up to 500 MW_e at a later stage, after the successful operation of the first unit. A feasibility study on the CSP incentive premiums required was completed in 2003 and was evaluated by the Israeli Public Utilities Authority (PUA) for a CSP and other renewable energy technologies feed-in law. A site for the first 100 MW was identified and approved, leaving space for enlargement up to 500 MW.

New Israeli feed-in incentives for solar IPPs are effective for 20 years from September 3, 2006. The tariff for the solar part is approximately 16.3 US cents/kWh (November, 2006) for over 20 MW_e installed capacity and a maximum fossil back-up of 30% of the energy produced.

The tariff for smaller plants in the 100 kW-to-20 MW range is about 20.4 US cents (November 2006)/kWh_e for the first 20 years.

On February 20, 2007, the Israeli MONI ordered a 250-MW_e CSP plant to be built at a site already approved in Ashalim, in the South of Israel. The Directorate General of MONI and the Finance Ministry have set up a bid committee. Public tender will be for a Build Own Operate (BOO) contract. In the next few months, an international call for tender for the construction of the 100-MW first stage solar plant will be issued.

As reported at the 71st SolarPACES ExCo meeting, following the new Israeli feed-in-law, a Rotem Industries-Solel joint venture is planning the erection of two 125-MW_e CSP modules in the northern Negev, currently awaiting final site approval by the Ministry of the Interior National Planning Authorization Committee. A decision was expected at the end of May 2007.

China

The Chinese National Development and Reform Commission 11th five-year plan 2006-2010 includes 200 MW of commercial CSP plants in the states of Inner Mongolia, Xin Jiang and Tibet, for which a 25-year power purchase agreement (PPA) will be offered.

A "solar thermal power technology and system demonstration" project is listed as Key Project 863 of the 11th Five-Year Plan 2006-2010 for National Hi-Tech R&D, administered and executed by the Institute of Electrical Engineering of the Chinese Academy of Sciences. Project 863 focuses on solar tower technology development and demonstration as a shorter route to local supply than parabolic-trough technology. Solar power tower plant technologies will be the focus of project research and demonstration, particularly emphasizing the characteristics of various concentrating and receiving technologies and power generation cycles. One of its specific projects is a 1-MW_e experimental solar power tower plant with a superheating water/steam receiver, 1-hour storage and auxiliary boiler.

Iran

With a rapidly expanding population, an urgent need to increase electricity production, and concern about atmospheric greenhouse gas build-up, the Islamic Republic of Iran has shown a growing interest in renewable energy technology, including solar power, and is keen to exploit its abundant solar resource by means of CSP technology. The government also wants to diversify its power production away from the country's oil and natural gas reserves.

In 1997, the Iranian Power Development Company contracted a comprehensive feasibility study on an Integrated Solar Combined Cycle with trough technology from the Electric Power Research Center (now the NIROO Research Institute) and Fichtner (now Fichtner Solar). Esfahan, Fars, Kerman and Yazd are all excellent regions for installing solar thermal power plants in Iran, but Yazd, where the entire high plateau is characterized by an annual direct normal irradiation of over 2,500 kWh/m^2/yr was finally selected as the site for the first plant.

South Africa

By 2010, the South African power utility, Eskom, could be operating the world's largest central receiver CSP plant. Eskom has studied both parabolic-trough and central receiver technologies to determine which is the cheaper of the two. It will employ local manufacturers of key components and is asking for estimates from local glass and steel manufacturers. Ultimately, a decision will be based on a variety of factors, including cost, and which plant can be constructed with the most local content. The project is currently assessing the feasibility of a 100-MW pilot project.

Italy

In 2001, the Italian parliament allocated €110 million for a CSP development and demonstration program. Since then, several parabolic-trough plants have been under development. In early 2004, ENEA and ENEL signed a cooperation agreement to develop the Archimedes Project in Sicily, the first Italian solar plant, which will be integrated in a thermoelectric combined cycle plant with advanced troughs using molten salt as the heat transfer fluid.

Australia

There are three main areas of solar thermal electricity generation in Australia. The most commercially advanced of these is the 35-MW Concentrating Linear Fresnel Reflector (CLFR) system to be incorporated into an existing coal-fired power station. Work commenced in July 2003. The first MW was completed and tested by September 2004. Solar Heat and Power is now developing a stand alone 240-MW design with its own turbine for installation at various sites around the world.

France

A new feed-in tariff for solar electricity was published on July 26, 2006, granting 0.30€/kWh (0.40€/kWh overseas) plus an extra 0.25€/kWh if integrated in buildings (+0.15€/kWh overseas). This tariff is limited to solar-only installations with less than 12-MW capacity and less than 1500 hours/year operation. For production over this limit the tariff is 0.05€/kWh. A first 12-MW CSP demonstration project is being promoted by the “Solar Euromed SAS” Company.

2.6 Tomorrow’s Markets

Economic operation of solar thermal power plants requires solar radiation of at least 1900 kWh/m^2 per year, which is found almost anywhere in the “Sunbelt”, that is, 35 degrees latitude either side of the Equator. With modern low-loss, low-cost, high-voltage DC transmission, electricity can be transported over distances of 2,000 to 3,000 kilometers at a grid cost of around 2 cents/kWh. Thus possible solar thermal power plant sites are within the transmission range of both developing demand in the third world and in the industrial demand of temperate zones.

A recent second edition of the 2003 CSP market study by Greenpeace International and the European Solar Thermal Industry Association in 2005 projected the ideal scenario, given the right market conditions, in 20 years from the base year of 2005 to the end of the second decade of the 21st century. It is not a prediction, but a scenario based on expected advances in solar thermal technology, and the growing number of countries which, driven by both climate change and power demand objectives, have policies fostering CSP projects.

From just 355 MW in 2005, total installation will have surpassed 6400 MW by 2015, and by 2025, the annual installation rate will be 4600 MW. At the end of the scenario period, the total worldwide installed capacity will have reached almost 37,000 MW. The scenario also estimated how much electricity could be produced by solar thermal power plants based on the assumption that the first facilities with only a small buffer storage system will operate for 2,500 annual full-load hours. However, later facilities will have an oversized collector field to collect more energy, which will not be used for direct electricity production, but for multi-hour storage systems for nighttime operation, increasing annual full-load operation to 3,500 hours per year in 2030 and 5,000 hours per year in 2040. By 2025, worldwide solar thermal power plants will have achieved an annual output of more than 95 TWh. The scenario assumed that during the early years, solar field capital investment, including all system costs, were about US$6,000/kW installed, fall gradually over the timescale of the scenario to almost half in 2025. This means that the investment in solar thermal power plants will fall from US$60 million in 2006 to US$16.4 billion in 2025.

2.7 Market Introduction Instruments and Policies

Solar thermal power plants have to compete in a well established, very competitive power market where older nuclear and fossil fuel power stations produce electricity at a marginal cost, because interest and depreciation on their investment have already been paid by consumers and taxpayers. Political action is therefore needed to overcome those distortions and create a level playing field where the economic and environmental benefits of solar thermal power can be fully exploited.

Without a political and financial boost, solar thermal power remains at a competitive disadvantage, mainly because of inadequate price information in the world’s electricity markets resulting from decades of massive financial and structural support for traditional, polluting fuels and power plant technologies.

Before project developers and CSP equipment suppliers can make long-term investments, a visible, reliable, and growing solar thermal power market with normal risks and acceptable investment costs, and thereby competitive rates, must exist. The CSP Global Market Initiative has identified some policy areas where impact on the use of concentrating solar power is the greatest:

Targets

For the GMI CSP goal for cost competitiveness of 5,000 MW_e by 2015 to be reached, national and/or regional CSP capacity targets must be set. These targets may be in terms of MW over time, or CSP percentage of new capacity to be built over a certain time, as in the Renewable Portfolio Standards.

Tariffs

CSP projects must have sufficient revenues to encourage private investment in a stable financial climate. This can be achieved by feed-in tariffs, production tax credits, or CSP-specific public benefit charges designed to diminish over time as the CSP technology becomes competitive, which should happen by 2015 when 5,000 MW_e of CSP have been installed. Coordination with neighboring countries, states or regions with preferential tariff schemes would make it possible to import CSP electricity from high solar radiation areas (where electricity costs are lower). The use of long-term power purchase agreements or similar long-term contracts with credit-worthy off-takers, or equity ownership by public organizations would build up the confidence of investors and financial institutions.

Financing

Bilateral and/or multilateral cooperation by financial institutions would ensure that project-related flexible Kyoto instruments such as Clean Development Mechanisms and Joint Implementation Actions are applicable to CSP and that these mechanisms are bankable. The establishment of national or regional loan guarantee programs through existing windows in multilateral banks, national lending programs and global environmental programs, such as the GEF, UNEP, and UNDP, would further reduce the inherent risk of introducing new technology for private-sector banking institutions.

Investment tax credits, which stimulated the first 354 MW of CSP plants in the United States, should be maintained and production tax credits similar to those that have stimulated the growth of wind power there should also be made available to CSP plants. Cost-shared transmission line development between regions with excellent solar resources and urban load centers, even across borders of participating countries and regions would optimize development and exploitation of all regional resources.

Regulation

Any limitations on CSP plant capacity or operating strategy making its introduction more costly must be avoided. Legal restrictions and barriers to cost-effective CSP plant connection to the electrical grid at end user (customer), distribution and/or transmission points must be identified and eliminated. Solar resources in immense areas of the North African Mediterranean and southwestern United States are unexploited. To exploit these energy resources, unimpeded grid connection must be guaranteed.

The most ambitious target has been set by the European Union. In 2001 the European Council and the European Parliament adopted a Renewable Energy Directive establishing national targets for each member state. Although these are not at present legally binding, the Directive aims at doubling the share of renewable energy sources in the primary energy mix from 6% to 12%, equivalent to 22% of Europe's total electricity consumption, by 2010. If this non-binding approach should appear not to be working, then the Directive allows the European Commission to submit proposals to the European Parliament and Council for mandatory renewable energy targets.

In the US, Renewable Portfolio Standards have been set in some states to gradually increase the contribution of clean, renewable power in the supply mix, which provide for penalization through compensation payments of utility companies failing to reach certain agreed targets. This mechanism, with initial targets for 2-5% of a state's total electricity demand by 2005 and 2010, respectively, is already starting to work. As a result, Nevada and Arizona are both negotiating long-term power purchase contracts for their first new solar thermal power plants.

A specific European policy mechanism which has enabled the achievement of renewable energy supply targets is the fixed tariff system or feed-in-law, where a specific tariff rate or premium is allocated to particular renewable technologies. These rates and premiums reflect the relative cost difference between the specific renewable technology and the price offered for bulk power on the liberalized power market. Utility companies must buy all renewable power produced at the rates established in the specific feed-in law. The differential cost of renewable power compared to the market price of bulk fossil or nuclear-generated electricity is borne by the electricity ratepayer.

The most successful feed-in law schemes have been set up in Austria, Denmark, Germany and Spain, with the most remarkable result that about 20,000 MW of wind power is currently on stream. Biomass and small hydropower plants are also increasing.

The Global Market Initiative for CSP has already structured the way for regional cooperation: Region II includes those countries that are or will soon be connected to Region I countries for transnational power exchange. Countries in Region II include Algeria, Morocco and Mexico. Solar power generated from CSP plants in these countries could be exported to Region I countries at a much more attractive price than generating it from the inferior solar resource in Region I. As a result of their excellent solar radiation resources and good grid connections, the southwestern USA and northern Mexico, as well as southern Europe and North Africa, would physically lend themselves for a cross-border trading of solar electricity. Region II participants will take the political initiative to formulate a fair scheme that accounts for both improved tariffs for clean energy generated in Region II countries and allows a benefit from enhanced feed-in tariffs for energy imported into Region I.

International solar thermal power plant technology projects can also profit from the Kyoto Agreement. In connection with "Joint Implementation" (JI) (among industrialized countries), CO_2 certificates can be transferred to the investor country. In the "Clean Development Mechanism" (CDM), projects are carried out between an industrialized country and a developing country. The goal is to economically develop the affected states while simultaneously reducing environmental pollution. Under the Kyoto Agreement, developing countries are not obligated to reduce emissions. Emissions reductions achieved through the project, however, can be transferred to the investor country as "Certified Emission Reductions" (CER). These can also be traded. Official emission trading is not scheduled to begin until 2008. Due to the lower avoidance costs for CO_2 emissions in developing countries, CDM projects are always very cost-effective for industrialized countries. Experts estimate the ratio of avoidance costs between developing and industrialized countries at up to 1:10. One of the essential requirements for CDM projects is "additionality", which means that reductions achieved must have been made possible by the CDM project. Solar thermal power plant technology is also ideal by this criterion. In this way, the Kyoto Agreement also promotes environmental protection in those countries that are not obligated to reduce emissions and offers potential investors financial incentives, and is therefore a mechanism that solar thermal power plant technology should exploit.

2.8 Conclusions and Outlook

Solar energy is the most plentiful and widely available form of renewable energy in the world. The solar irradiation on the Earth is about 10,000 times the world energy demand. Large-scale solar thermal power plants of up to 200 MW are ready for the market and can replace conventional power plants operated in the medium-load range without any qualitative changes in the grid structure. Solar thermal power plants receive their energy from the same source that causes summer air conditioning peaks – the sun – and are therefore perfectly compatible with summer peak loads.

Solar thermal power plants can be designed for solar-only generation, ideally to satisfy a peak load demand, as they can dispatch power as needed during peak demand periods, but with storage systems, up to an annual average 100% solar share could be achieved in the future.

Solar thermal power plants can be operated profitably throughout the Earth's Sunbelt, which includes southern Australia, Europe, the southern Mediterranean, Middle East, Asia, South America and the southwestern United States.

The CSP sector has recently revived after its first market success in the late 1980s. Industrial involvement is still in its infancy with large construction companies being the first to take on the risk in implementing commercial plants. Utilities and large power companies are still reluctant and pending technical and commercial success before making their own investment in the technology. 2007 CSP technology is based mainly on the concepts of the commercial projects implemented in the early

1990's. In Spain, France, and the US, the sector is communicating through national and European industry and developer associations. The emerging market has already attracted key component manufacturers to invest in new manufacturing facilities in Europe.

The goal is for the cost of solar energy to be competitive with fossil fuels. The forecast is for intermediate-load electricity to cost less than 15 US cents/kWh by 2020 in sun rich regions with over 2500kWh/m²/yr..

Implementation of feed-in tariffs must be accelerated in a number of other countries. Many of the existing regulations still discriminate against CSP power. EU directives are required.

An open renewable electricity market, in which electricity is imported and exported by member states and also from outside is necessary to ensure that least-cost renewable electricity can be generated where resources are best. This will increase CSP market opportunities.

An HVDC super-grid to make effective use of renewable electricity produced where resources are the best would lead to a least-cost renewable energy mix. Investment in such grids can only be achieved if the market has a clear and reliable long-term perspective.

Technological breakthroughs need to be demonstrated in large-scale demonstration projects. This includes higher temperature technology, innovative thermal storage systems and new solar turbine systems that are adapted to solar operating conditions. These projects have not evolved from the existing technologies, but are rather a new step in the technology comparable to other technology sectors, such as the change from steam cycle to combined cycle power plants or onshore to offshore wind energy.

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Part 3: Status Report
Task I:
Solar Thermal Electric Systems

Operating Agent:
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3 Task I: Solar Thermal Electric Systems

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. These are separated into sub sectors, as designated by the Operating Agent and approved by the Executive Committee. Each sector is coordinated by a Sector Leader who is appointed by the Operating Agent and is responsible for coordinating activities within his Sector. Historically, these sectors have been described by 1) Central Station Systems, 2) Distributed Generation Systems, and 3) CSP Market Development. In 2006, the SolarPACES ExCo requested that the Task propose a revised structure with the intent of meeting the needs of a growing CSP industry and market. The outcome was a proposed structure that will emphasize worldwide project or system level data dissemination as well as the development of standard methodologies for collection of such data. Efforts are underway to support this reorganization. This year's Task I report will focus on descriptions of newly operating systems, systems under construction, or systems under development. These descriptions are based on requests for information to individual project developers. As such, they do not necessarily represent all projects under development to the degree that some participants choose not to provide a response.

Deliverables: The OA is responsible for general Task I reporting, including preparation of input to the IEA/SolarPACES Annual

Report, and for maintaining a Program of Work describing ongoing and anticipated activities. Participants are responsible for detailed reporting on their respective activities. General reports (not containing proprietary information) are available to all Task participants, although the Participants in an activity may, at their option, limit the distribution of proprietary information. The activity lead is responsible for providing information to the OA for general reporting requirements. The OA is responsible for organizing one to two Task meetings per year to discuss activity status and progress.

One Task I meeting was held in 2006 in Sharm El-Shiek, Egypt in conjunction with the Task III meeting.

3.3 Status of the Technology

Concentrating solar power offers the lowest cost option for solar energy today, with expected production costs of less than 20¢/kWh for early commercial plants with lower costs 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.

Concentrating solar power today is basically 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 (construction of a small 1MW ORC trough plant was completed by SolarGenix for Arizona Public Service in 2005). Abengoa inaugurated PS10, an 11MW saturated steam central receiver plant located near Seville, Spain. Three additional plants, Andasol One, Andasol Two, and PS20 are under construction in Spain. Andasol One, a 50 MW parabolic trough plant with 6 hours of thermal storage, is expected begin operating in 2008. Andasol Two, identical in design, is expected to begin operation in 2009. PS20, a 20MW tower similar in design to PS10, is expected to co begin operating in 2008. Many other projects are under various stages of development, primarily in Spain, northern Africa, and the southwest U. S.

The Chapter dealing with solar thermal power plants by Becker et al. in "*The future for Renewable Energy 2: Prospects and Directions*" edited by the EUREC Agency in 2002, provides a thorough, up-to-date summary of the status of the technology, a look at the road to the future, market inroads, and goals for

RD&D, as seen from the standpoint of selected experts of the SolarPACES community. Chapter 6 of Volume 16 of the American Solar Energy Society (ASES), Advances in Solar Energy, written by Price and Kearney [3.06] provides a comprehensive discussion of the current status and future cost reductions related to parabolic trough technology.

Parabolic troughs are today considered to be a 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 based on the current generation of heat collection elements being furnished to the plants by both Solel and Schott. Several commercial trough projects are being pursued in Spain. The first one under construction is the 50-MW Andasol One project that will use EUROTrough collectors and will have a 6-hour molten-salt heat storage system. Construction of the Andasol project near Granada began in 2006, with commissioning planned for 2008. Construction of Andasol Two, identical in design to Andasol One, began construction in 2007 with commissioning planned for 2009.

In the United States, two commercial parabolic-trough power plant projects are operational. The first is a 1-MW organic-rankine-cycle plant built by SolarGenix for Arizona Public Service. An organic Rankine cycle operates at lower temperature and efficiency than a steam-Rankine cycle and, potentially, will require lower operating and maintenance staffing. Construction was completed in December of 2005 and the plant started operation in January of 2006. Abengoa, formerly SolarGenix, completed construction of a 64-MW trough project (conventional hot oil with a Rankine cycle power block) in Boulder City, Nevada (near Las Vegas). Operation of that plant began in June of 2007.

Several options for hybrid solar/fossil plants exist. The integrated solar combined-cycle system (ISCCS) using trough technology has received much attention in the past few years. Its advantages are lower near-term cost and risk of solar electricity, but this design's small annual solar fraction of about 10% is of concern to some [3.28]. New Energy Algeria (NEAL) selected Abener 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 consideration in Egypt, Mexico, Morocco, and India.

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 based heat transfer fluids. Research on higher-temperature heat transfer fluids and lower cost storage systems are also being pursued.

Linear Fresnel systems are conceptually simple, using inexpensive, compact optics, and are being designed to produce saturated steam at 150-360 C with less than 1 Ha/MW land use. This technology may be suited for integration into combined cycle recovery boilers; i.e., to replace the bled extracted steam in regenerative Rankine power cycles or for saturated steam turbines. The most extensive testing experience at a prototype-scale is underway at the Liddell power station in Australia with very compact designs using multi-tower aiming of mirror facets. The first large proof-of-concept facility will be a commercial project started by the Solar Heat & Power Company, now Ausra, to integrate 36 MW of solar into an existing coal-fired power plant. In this hybrid plant, the 132,500-m^2 reflector field will supply 270°C heat to replace bled steam in the regenerative feed water heaters of the Rankine power cycle. Late in 2006, a 300 meter long array (5 MW_{th} delivery) was installed at the site. This is the first of three such arrays planned for this project stage. Connection to the Liddell plant is expected in 2007.

Power towers 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. The most extensive operating experience has been accumulated by several European pilot projects at the Plataforma Solar de Almería in Spain, and the 10-MW Solar One and Solar Two facilities in California. After continuous technology improvement, CRS technology is predicted to reach efficiencies of 23% at design point and 20% annual performance.

Construction of PS10, the first commercial power tower, was completed by Solucar at its project site outside of Seville, Spain. The tower system uses a saturated steam receiver, producing 40 bar/250ºC saturated steam to power an 11-MW saturated steam turbine. The plant has a 20-MWh capacity thermal-oil storage system (1/2 hour at 70% load) for cloud transients. Solucar has initiated construction of a second 20-MW system similar in design to PS10. PS20 is scheduled to become operational in 2008.

An alternative to steam systems such as that developed for PS10 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 is projected to achieve energy costs similar to trough systems in Spain, but with higher investment risk. Larger increases in plant size are projected to reduce energy costs significantly, with potential for achieving costs below that of advanced trough technology. Solar Tres, a 17 MW molten-salt tower under development by Sener, is projected to start construction in 2008. Another molten-salt plant at 100 MW is also under consideration in South Africa.

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 largere, 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. The EnviroDish project aims to transfer the former Eurodish system into small series production and deploy systems around the world.

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.

3.4 Program of Work in 2007

The focus of our efforts is on the testing of integrated CSP systems and support of commercial deployment projects. Systems listed in the table below (with contact person) are de-

Table 3.1 Reported Task I activities

COMMERCIAL CSP SYSTEMS	**Contact**	***Sharing***			
		I	**M**	**T**	**C**
Operational Systems					
PS10	Valerio Fernández Quero	x			
NEVADA SOLAR ONE	Gilbert Cohen	x			
Systems Under Construction					
PS20	Valerio Fernández Quero	X			
ANDASOL 1	Antonio Gómez + Marcelo Formica	X			
ANDASOL 2	Antonio Gómez + Marcelo Formica	X			
LA RISCA ONE	Jose Monzonis	x			
IBERSOL CIUDAD REAL	Cristina Heredero Bueno	x			
SOLNOVA	Valerio Fernández Quero	X			
EXTRESOL-1	Antonio Gómez	x			

scribed in more detail in Section 3.6 below. In the sharing column, “I” refers to information sharing; “M” to task sharing by member countries; “T” to task sharing through SolarPACES; and “C” to cost sharing.

3.5 Participation and National Contributions

Task I is open to all IEA/SolarPACES member. Participation requires active involvement in an appropriate activity as described by the scope of Task I. Currently, all SolarPACES member countries except Switzerland participate in Task I.

3.6 Summary of Projects in Operation or Under Construction in 2007

NEVADA SOLAR ONE

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Participants: Acciona Energia, Acciona Solar Power, Acciona North America, Solargenix Energy.

On January 31 2007, Nevada Solar One (NSO) the 64-MW parabolic trough built in Boulder City achieved its seventh month of commercial operation and produced over 57,000 MWh.

NSO is the largest solar energy project to be built in the United States since 1991. It is also the largest renewable generating facility to be built in the State of Nevada. NSO, with a nominal capacity of 64 MW will produce over 130,000 million KWh annually. NSO was initially developed by Solargenix Energy in 2003 and was jointly owned by Acciona Energia and Solargenix Energy. Acciona Energia purchased 55% of Solargenix Energy forming a new company called Acciona Solar Power.

The power plant is composed of 357,000-m^2 second generation parabolic troughs (SGX2) developed by Solargenix Energy in collaboration with the National Renewable Energy Laboratory. The SGX 2 has an improved space-frame design and is the natural development of SGX 1, which was successfully used in the 1-MW Saguaro plant in Arizona. The new space frame was redesigned to reduce manufacturing time and cost. The SGX2 collector is extremely accurate, light and easy to assemble, without a complicated and expensive fabrication jig. After seven months of operation, nearly zero mirror or receiver tube breakage demonstrates that the goals set for the space-frame design were effectively accomplished. This is a significant improvement in solar field reliability over historic SEGS data.

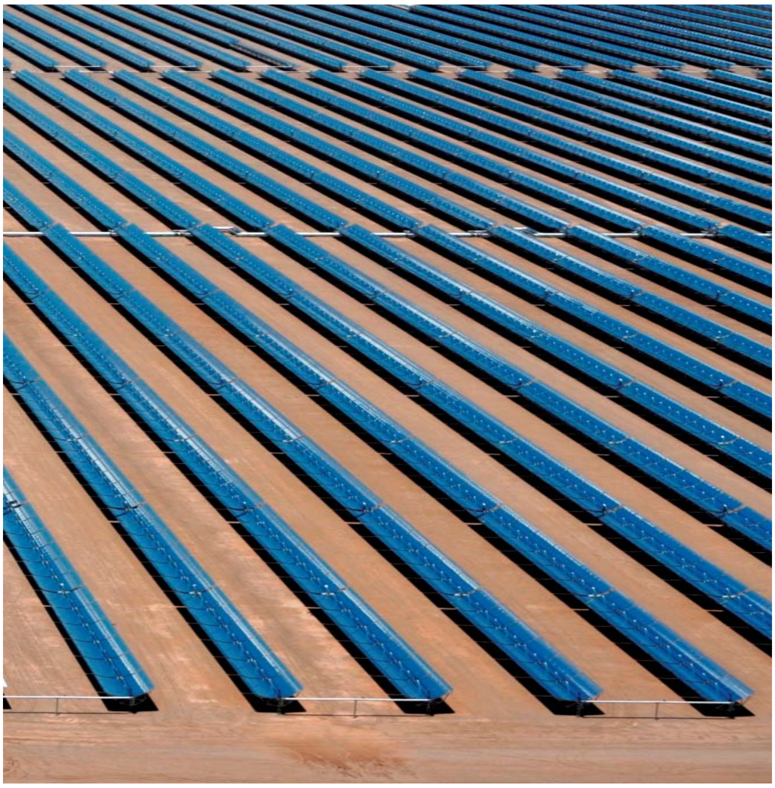

Figure 3.1 NSO Solar Field – Acciona Solar Power

The power block, located on the west side of the property, has a Swedish Siemens 70-MW reheat steam turbine. Only a 2% supplement is allowed in Nevada, therefore the plant has only a very small natural gas heater, mostly for freeze protection. NSO is a solar-only system with 30 minutes of thermal storage used to minimize transients. This “built-in” thermal storage is very effective. Operators have successfully run the plant for more than one hour after sunset.

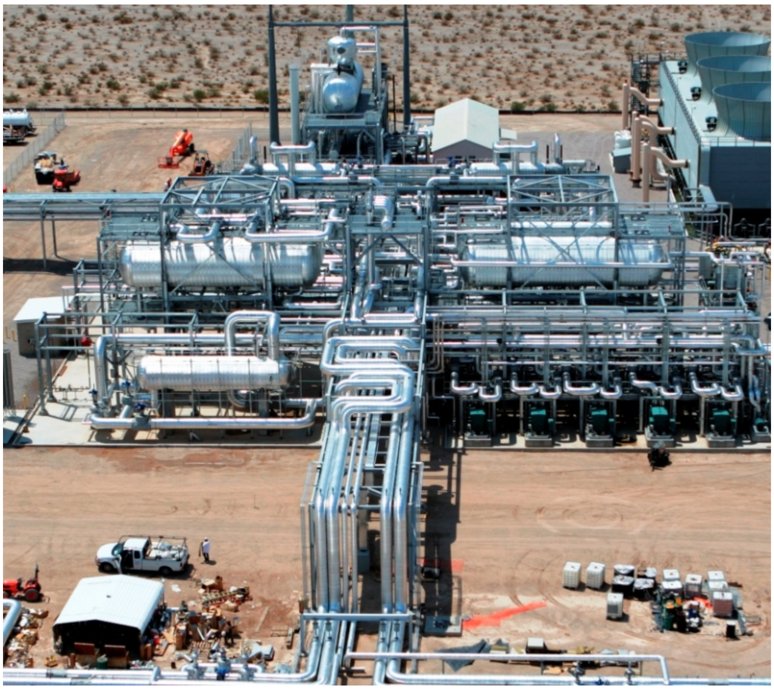

Figure 3.2 NSO Power Block – Acciona Solar Power

PS10, First Commercial Concentrating Solar Tower in Operation

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Participants: Abengoa Solar (E), collaboration of Ciemat (E), DLR (D), Fichtner (D)

Funding: 40.0 M € investment, (33.8 M € from equity, 5.0 M € grant from European Commission Fifth Framework Programme, 1.2 M € grant from the Andalusia Regional Government Renewable Energy Program)

PS10 is an 11-MW solar thermal power tower plant in commercial operation since June 2007. Promoted by Abengoa Solar, it is located at Solúcar Platform in Sanlúcar la Mayor, 15 km west of Seville (Lat: 37º 26' N, Long: 6º 14' W).

The PS10 solar field consists of 624 120-m2 (1291 sq.ft.) Sanlúcar-120 heliostats, which means the entire heliostat field has an area of 75,000 m2. Heliostats track the sun on two axes and concentrate the radiation onto the receiver located on the upper part of the 115-m (377 ft) tower.

PS10, including its receiver with direct saturated steam generation, was designed by Abengoa Solar NT. The receiver is composed of four 5.5 m (18 ft) wide by 12 m (39 ft) high vertical panels. The panels are arranged in a semi-cylindrical configuration inside an 11 m x 11 m (36 ft x 36 ft) cavity. At design conditions, the receiver delivers 55 MWth of saturated steam at 257ºC (495ºF). The solar-to-steam conversion efficiency is over 90%.

The PS10 solar plant has thermal storage for over 30 minutes of full-load generation. Thermal storage can boost power production under low radiation conditions. PS10 can also use natural gas for 12-15% of its electrical production. The PS10 will generate 24.3 GWh per year. As shown in the schematic below, the steam produced by the PS10 solar field operates a conventional power cycle.

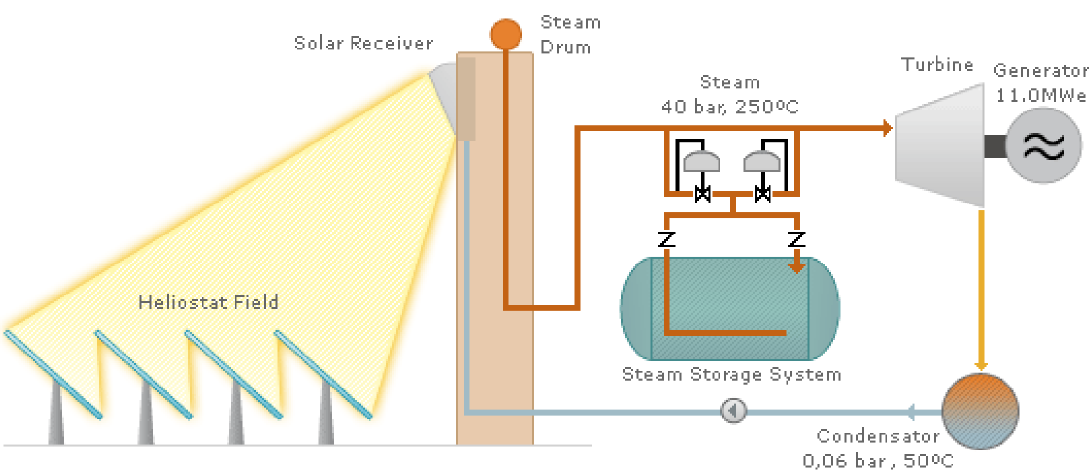

Figure 3.3 PS10 Schematic Diagram

Figure 3.4 Aerial view of PS10 in operation and PS20 under construction.

PS10 started to generate solar electricity on February 28, 2007, and was officially inaugurated in a public event on May 30th.

Commercial operation started on June 20, 2007, with 72 hours of performance tests resulting in 112% of expected generation. PS10 produced over 10.6 GWh of electricity from July to December 2007, which is about 86% performance efficiency in its first six months of commercial operation. Operating experience acquired and improvements in aiming strategies with spillage reduction have led to plant operation at 100% of expected efficiency late in 2007.

PS20, A 20-MW Commercial Concentrating Solar Tower under Construction

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Participants: Abengoa Solar (E)

PS20, a 20-MW solar thermal power tower plant for commercial electricity production, is scheduled to start operation in the second half of 2008. Promoted by Abengoa Solar, it is the second solar thermal plant at the Solúcar Platform in Sanlúcar la Mayor, Seville, Lat: 37º 26’ N, Long: 6º 14’ W, which will have a capacity 300 MW by 2012.

The PS20 solar field is composed of 1255 120-m^2 (1291 sq ft) Sanlúcar-120 heliostats, which means the entire heliostat field has an area of 150,600 m^2. Heliostats track the sun on two axes and concentrate the radiation onto the receiver located at the top of the 165 m (541 ft) tower.

Figure 3.5 Aerial view of PS20 under construction with PS10 in the background.

PS20 was designed by Abengoa Solar NT for the direct generation of saturated steam.

The solar plant includes a thermal storage system for over 30 minutes full-load generation. Thermal storage can boost power production under low radiation conditions. PS20 can also use natural gas for 12-15% of its electrical production. The PS20 will generate 50.6 GWh per year. The steam produced by the PS20 solar field operates a conventional power cycle with the same main parameters as the PS10 plant.

PS20 construction was well advanced at the end of 2007. Over 60% of the heliostat field was installed, the solar tower, and many power infrastructures, including the cooling towers. Operation is due to begin by October 2008.

ANDASOL-1

<u>Contact</u>: Antonio Gomez (ACS-Cobra)
Marcelo Formica (Solar Millennium)

<u>Participants</u>: Flagsol, ACS-Cobra, SENER

<u>Funding</u>: ACS-Cobra, Solar Millennium

The Andasol 1 parabolic-trough power plant now under construction in Aldeire, Granada (Spain), scheduled for completion in summer of 2008, will be the first parabolic-trough power plant in Europe. It is being promoted by Solar Millennium AG in cooperation with the Spanish ACS/Cobra Group. The plant will supply environmentally-friendly solar electricity to some 200,000 people. Solar Millennium AG started Andasol-1 project development in the late 1990s. The corporation concluded a partnership with the ACS/Cobra group, Spain's largest construction and power plant engineering company, which in December 2004, entered the 300 million-Euro project by purchasing 75% of the shares of Andasol-1 S.A. The remaining 25% is owned by a group of German investors represented by Solar Millennium. Making use of Solar Millennium experience, the ACS/Cobra group is responsible for its construction. Flagsol GmbH, the technology subsidiary of Solar Millennium AG, provides the engineering for the solar field, i.e., planning, design and construction supervision and control.

Table 3.2 At a glance – the power plant data sheet of an Andasol power plant

Electrical Capacity	50 MW
Capital expenditure	~ 300 million Euros
Electricity output	~ 176 GWh /year
Power plant dimension	2 km²
Surface area of the collectors	510,000 m²
Thermal storage system	28,500 tn salt, sufficient for 7.5 hours at 50 MW power output
Solar power	supply 200.000 people
Construction period	two years
Number of employees during construction	up to 500
Number of employees when in service	about 40

ANDASOL-2

Contact: Antonio Gomez (ACS-Cobra), Marcelo Formica (Solar Millennium)

Participants: Flagsol, ACS-Cobra, SENER

Funding: ACS-Cobra, Solar Millennium

The Andasol-2 Project, now under construction, is identical to Andasol-1, and is due for completion by the end of 2008, also in Aldeire, Granada (Spain).

LA RISCA ONE

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Participants: Acciona Energia, Acciona Infrastructuras, Acciona Solar Power

Funding: Acciona Energia

La Risca One, located in LA RISCA, Badajoz Province, Spain, is a 50-MW parabolic-trough solar plant similar to the Nevada Solar One (NSO) project completed in 2007 by Acciona Solar

Acciona Energia

Figure 3.6 La Risca – Grading (February 2008)

Power. Project construction started in February 2008, and all equipment was procured in 2007. Commissioning and startup are scheduled for early 2009.

The power plant is composed of 360,960 m² of SGX 2 solar collectors developed by Acciona Solar Power (formerly Solargenix Energy). The space frames are identical to those used at the NSO project in Nevada. The majority of the reflector panels are by Flabeg (Germany), other reflectors will be located on the field perimeter for better wind protection. The receiver tubes were manufactured by Schott Glass.

The power block, located on the west side of the solar field, has a 49.9-MW net-capacity Swedish Siemens reheat turbine. “Built-in” 30-minute thermal storage is provided by extended header piping.

In normal operation, a heat transfer fluid, or HTF, circulates in the solar field and is heated up to 395ºCelcius before entering a series of heat exchangers to produce steam. The steam is then expanded in the steam turbine, driving a generator and producing electricity. Reheat steam generator efficiency is expected to be as much as 38%.

IBERSOL CIUDAD REAL

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Participants: Iberdrola Renovables (E), IDAE (E).

The Ibersol Ciudad Real Project consists of the design, construction and operation of a 50-MW parabolic-trough solar thermal plant located 9 km from Puertollano (Ciudad Real) and 240 km south of Madrid.

Figure 3.7 Aerial view of IBERSOL under construction

Iberdrola Renovables, through Iberdrola Energía Solar de Puertollano, 90% owned by Iberdrola Renovables de Castilla-La Mancha (IBERCAM) and 10% by IDAE, is responsible for plant construction. The project is wholly financed by the company's own resources.

The following plant processing milestones have been achieved: provisional REPE granted, DUP requested, resolution of no need of DIA, building license granted, grid connection granted, agreement with Town Hall for water supply, authorization to discharge water into the Ojailén River applied for with the Confederación Hidrográfica del Guadalquivir (CHG), agreement with Gas Natural Distribución for gas supply and access to the plant from the CR-504 road has been granted.

The plant's predicted output is 114 GWh/year with an estimated operating time of 2,062 hours. The plant will consume 570,000 m^3/year of water.

The Puertollano Plant solar field of 88 Eurotrough parabolic-trough collector loops covers approximately 135 ha of land. Each collector loop is made up of 4 collectors approximately 150 metres long, connected in series, for a total of 352 collectors. The solar field has 12,700 absorber tubes and around 120,000 mirrors with a collection surface of approximately 287,760 m^2.

The Eurotrough collector has a modular galvanized-steel structure made up of 12 5.76-m-wide 12-m-long modules. 28 reflector mirrors are attached to this module structure, and each module has 3 absorber tubes.

Unlike conventional thermal power plants, in a solar thermal plant, instead of a boiler, there is a solar field of parabolic-trough collectors. These collectors are composed of reflector support structures having a parabolic shape that concentrates the solar radiation in the parabola's line of focus. Thermal oil flowing inside an absorber tube in the line of focus is heated up to approximately 400ºC. The heat of the oil is transferred to water which is then transformed into steam in a steam generator. The steam is sent to a double-casing (high and low pressure) condensing turbine with extraction points for pre-heating the

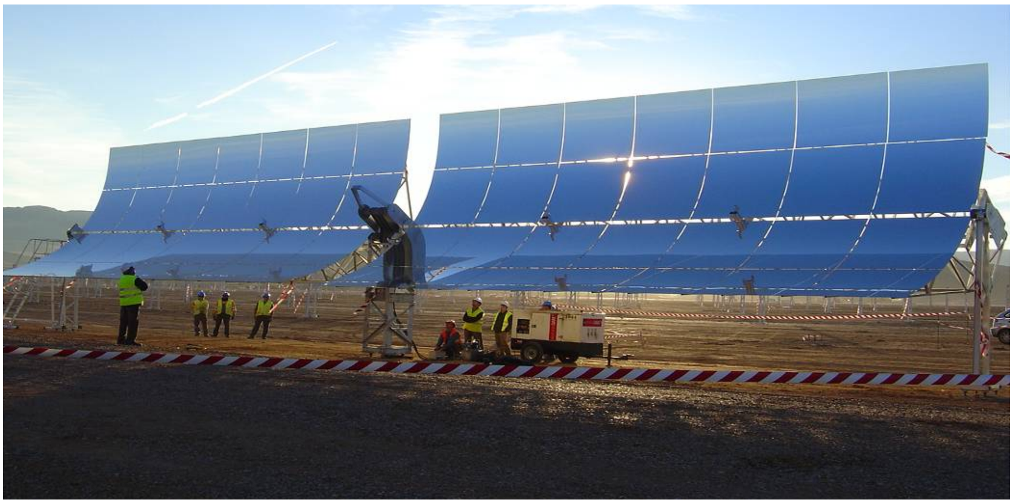

Figure 3.8 Erection of collectors

condensate and feed water for the steam generator. Finally a generator coupled to the steam turbine generates electricity.

The Puertollano solar thermal plant has an auxiliary support oil heater system, which enables the power output to be regulated during periods of low solar radiation, plant shutdowns and transients. The auxiliary system, fired by a fossil fuel, provides energy to the plant in parallel with the solar field. This fossil fuel consumption is limited by Spanish Royal Decree 661/2007 to 15% per year.

The collectors rotate around their longitudinal axis, guided by a single-axis solar tracking system to achieve the optimal reflector position. This system maximizes the time that the collection surface is exposed to direct solar radiation. The solar tracking system includes solar position sensors, hydraulic drive, and local controller programmed with solar tracking algorithms.

Work began in March 2007 and commissioning is planned for December 2008. The plant is currently under construction and earth moving of the solar field is almost concluded, 50% of solar foundations are completed, foundations of main BOP equip-

Figure 3.9 Artist's view of the future IBERSOL plant

ment (turbine, cooling towers, tanks, etc.) has been executed, the warehouse has been built and on-site assembly and erection of collectors has begun. Procurement of equipment and services is almost complete. Some of the main suppliers are: Siemens (turbine), Schott and Solel (absorber tubes) and Flabeg and Rioglass (reflectors).

Solnova 1, First of 5 50-MW Parabolic Trough Plants at Solúcar Platform, under Construction

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Participants: Abengoa Solar (E)

Solnova-1, which has a 50-MW capacity, is the first of five 50-MW parabolic trough plants that will be constructed by Abengoa Solar at the Solúcar Platform in Sanlúcar la Mayor, Seville, Spain (Lat: 37º26’ N, Long: 6º14’W).

Solnova 1 has a design power rating of 50 MW. Based on the local solar resource, the plant is predicted to deliver 114.6 GWh of clean energy per year. That is enough to supply 25,700 homes and to reduce CO_2 emissions by over 31,200 tons per year. To supplement power generation under low solar radiation, Solnova 1 is also equipped to burn natural gas to deliver 12-15% of the plant output. At peak conditions, the plant converts available solar radiation into heat with an efficiency of nearly 57%. Combined with the steam cycle efficiency, overall plant efficiency is approximately 19%.

As shown in Figure 3.10, the parabolic-trough solar field heats synthetic heat transfer oil. Energy in the oil is used to generate

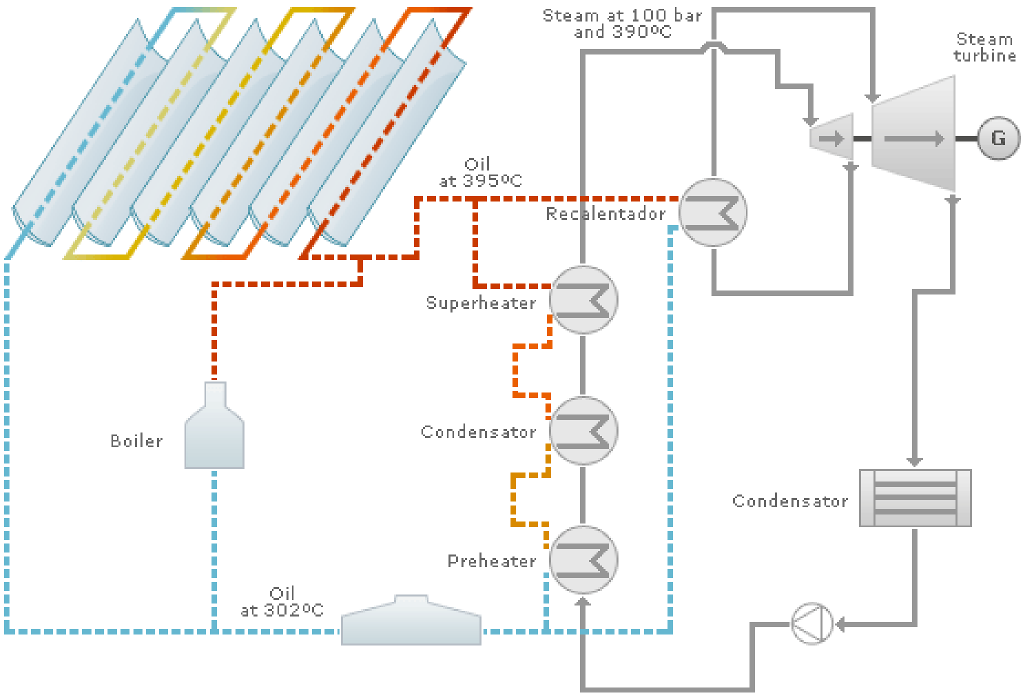

Figure 3.10 Schematic diagram of Solnova 1

Figure 3.11 Aerial view of Solnova-1 under construction with PS10 in operation and PS20 tower visible in background

superheated, high pressure steam that is delivered to a steam turbine. This turbine powers a 50-MW-capacity electrical generator.

The Solnova 1 plant has 90 loops with four trough collectors in each. Each collector is composed of 12 connected 12.5 m (41 ft) long by 5.76 m (18.9 ft) wide modules. A drive mechanism located at the center of each collector tracks the sun on one-axis. Rows of collectors are separated to avoid row-to-row shading and for maintenance access.

By the end of 2007, land preparation was completed and collector foundations were ready to be started, as shown in the picture below. Solnova is due to start production in the second half of 2009.

EXTRESOL-1

Contact: Antonio Gomez (ACS-Cobra)

Participants: ACS-Cobra, SENER

Funding: ACS-Cobra, Cajamadrid

Extresol-1, under construction in Torre de Miguel Sesmero, Badajoz (Spain), is based on the same Technology concept as Andasol 1 and Andasol 2. Completion is scheduled for summer 2009.

Part 4: Status Report
Task II:
Solar Chemistry

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Anton Meier
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4 Task II: Solar Chemistry

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4.1 Nature of Work & Objectives

The Solar Chemistry Annex encompasses activities that deal with solar-driven thermochemical and photochemical processes for:

- Production of energy carriers
- Processing of chemical commodities
- Detoxification and recycling of waste materials.

Solar energy can be converted into chemical fuels, which can be stored long-term and transported long-range. Solar energy can also assist in the processing of energy-intensive and high-temperature materials, and in the detoxification and recy-

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cling of waste materials. These are examples of applications of solar chemistry for addressing the energy and environmental problems facing the world.

The Solar Chemistry Annex aims at coordinating international efforts towards research, development, and demonstration of solar chemical technologies through cost, task, and information sharing activities. This goal is being achieved by making use of an efficient network, through National Coordinators (NCs), for the rapid exchange of technical and scientific information. In 2007, we welcomed Alfonso Vidal as the new NC for Spain. We gratefully acknowledge the service of the former NC, Julian Blanco.

In 2007, nine papers were presented on solar chemistry and hydrogen production research were presented at a major international conference, the *ASME Energy Sustainability Conference*, Long Beach, CA, USA, June 27-30, 2007.

The following chapter summarizes the most important achievements in 2007 and provides a comprehensive overview of the many ways in which solar chemical technologies may be used for the delivery of clean, sustainable energy services.

4.2 Status of Technology

Systematic development of three solar concentrating optical configurations, trough, tower, and dish, has led to the ability to harness concentrated solar energy efficiently, producing fuels and chemicals for the power, transportation and chemical sectors of the world energy economy. Non-concentrating solar technologies may also be applied advantageously to photochemistry. Research is classified according to its objectives into three domains (sub-tasks):

Task II.1. SOLAR PRODUCTION OF CHEMICAL ENERGY CARRIERS: Solar hydrogen; solar reforming of natural gas; solar reduction of metal oxides; solar conversion of carbonaceous materials; solar cracking of hydrocarbons; solar chemical heat pipes.

Task II.2. SOLAR PROCESSING OF CHEMICAL COMMODITIES: Solar production of metals, hydrogen, synthesis gas, carbon filaments, fullerenes, lime, cement, and other fine and bulk chemicals.

Task II.3. SOLAR DETOXIFICATION AND RECYCLING OF WASTE MATERIALS: Solar detoxification and recycling of hazardous waste and of secondary raw materials.

The most important achievements in 2007 are summarized with up-to-date information about project participation, objectives, status, and relevant publications. The focus of the work was on Task II.1 SOLAR PRODUCTION OF CHEMICAL ENERGY CARRIERS, in particular hydrogen and synthesis gas. Part of the activities of Task II.3 SOLAR DETOXIFICATION AND RECYCLING OF WASTE MATERIALS, namely detoxification and disinfection of contaminated water, will be covered within the newly created Task VI on Solar Energy and Water Processes and Applications.

4.2.1 Solar Production of Energy Carriers

SOLREF – Solar Steam Reforming of Methane Rich Gas for Synthesis Gas Production

Participants: DLR (D), APTL (GR), WIS (IL), ETH (CH), Johnson Matthey Fuel Cells Ltd. (UK), HyGear B.V. (NL), SHAP S.p.A. (I)

Contact: Stephan Möller, stephan.moeller@dlr.de

Funding: EC funded project, cost shared: € 2,100,000

Duration: April 1, 2004 - March 31, 2009

Background: The work proposed in SOLREF is based on the activities performed in the previous SOLASYS project, in which the technical feasibility of solar steam reforming was proven. Based on the experience and know-how acquired in SOLASYS, SOLREF will take solar steam reforming a significant step closer to industrialization.

Objectives: The main purpose of this project is to develop and operate an innovative 400 kW_{th} solar reformer for several applications, such as hydrogen production or electricity generation. The new solar reformer will be more compact and more cost-effective than the previous SOLASYS reformer.

Achievements in 2007: Due to delay in the manufacturing/certification of the reformer, the project is being extended to March 2009. The components of the 400-kW_{th} solar reformer are now manufactured (Ref. [4.1]). The vessel and the front flange are certified. Reformer component assembly is scheduled for February 2008. Figure 4.1 presents first market potential estimates and possible solar reforming plant sites in Algeria. About 72,000 TWh/yr (areas in yellow and red, along existing NG-pipelines) can be used in Algeria for solar H_2 production. This is more than enough for renewable production of today's worldwide H_2 demand.

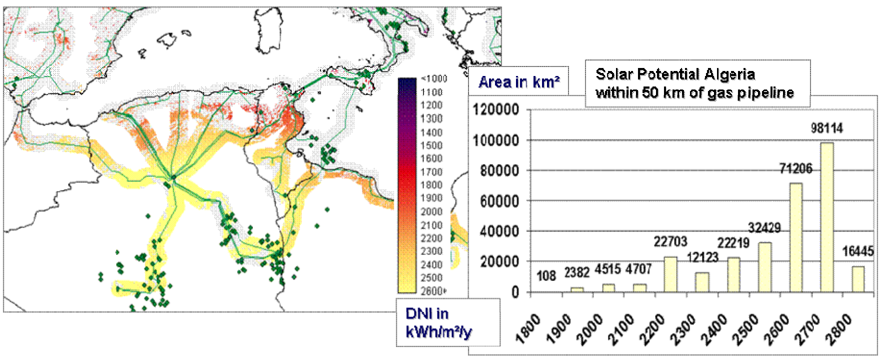


Figure 4.1 Potential market and possible locations for solar reforming plants.

A nonlinear dynamic model was developed for the steam/methane-reforming reactor, which uses concentrated solar radiation as the source of high-temperature process heat (Ref. [4.2]). The model incorporates a set of lumped-parameter reservoirs for mass and energy. Unsteady mass and energy conservation equations, coupling conduction, convection, and radiation heat transfer with temperature-dependent chemical conversion, are formulated for each reservoir. Radiative exchange, the dominant heat transfer mode at above 800 K, is solved by a band-approximation Monte Carlo technique. The dynamic model was applied to predict the transient behavior of the 400-kW_{th} prototype solar reformer in purging, thermal testing, startup, chemical reaction, shutdown, and cyclical operating modes. Time constants vary from 2 s for species transport to 10^5 s for thermal energy transport through ceramic insulation. Validation will be by comparing modeled outlet gas temperatures with experimental measurements in solar tower reactor tests.

A 3D digital representation of a reticulate porous ceramic (RPC) sample, generated by computer tomography (CT), was employed to determine its porosity, surface-to-volume ratio, and the minimum size of a representative elementary volume (REV) for continuum domain (Figure 4.2, Ref. [4.3]). Afterwards, the extinction coefficient and scattering phase functions were calculated using the Monte Carlo (MC) ray-tracing technique based on the probabilistic distribution functions of the extinction path-length and of the directional cosine of incident radiation. The methodology and governing equations were presented for diffusely and specularly reflecting surfaces. The isotropic assumption was justified by demonstrating that the extinction coefficient is directionally independent.

<u>Publications</u>: [4.1]-[4.3]

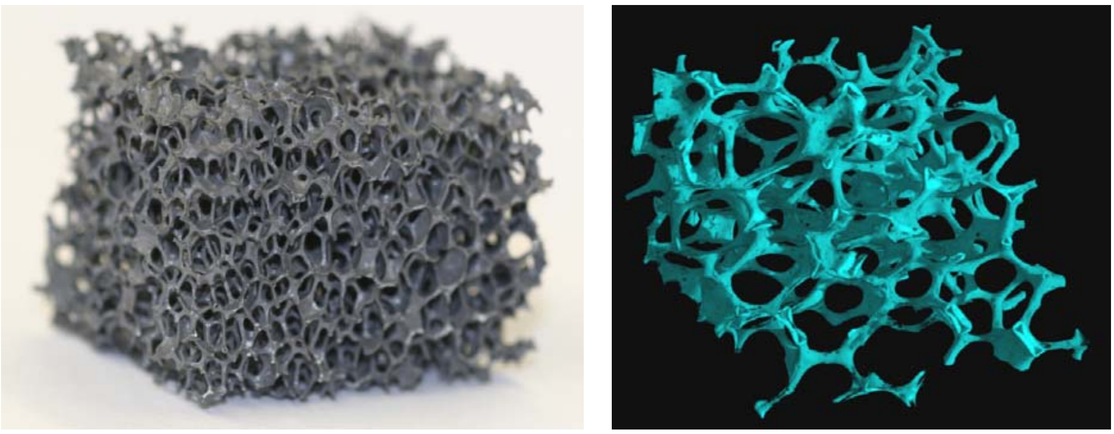


Figure 4.2 Left: Photograph of a 30 x 35 x 43 mm^3 cuboid sample of reticulate porous ceramic (RPC) used to obtain computer tomography (CT) scans. Right: 3D surface rendering of the 15 x 15 x 9 mm^3 central region of the foam skeleton. Ref. [4.3].

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

<u>Participants:</u> 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)

<u>Contacts:</u> Gilles Flamant, flamant@promes.cnrs.fr

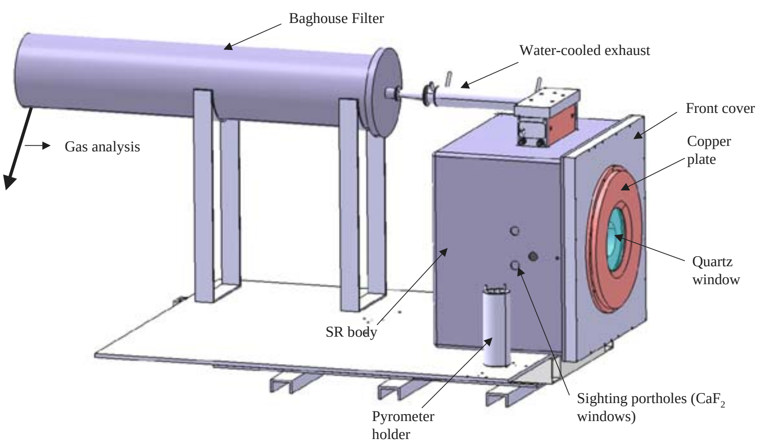
<u>Funding:</u> EC-funded project, cost-shared: € 2,000,000

<u>Duration:</u> March 1, 2006 – February 28, 2010

<u>Background:</u> The solar cracking of natural gas offers a viable route for fossil fuel decarbonization and is a mid-term transition towards solar hydrogen without greenhouse gas emission. Using solar energy for process heat offers a threefold advantage: (1) the discharge of pollutants (e.g. CO, CO_2, NO_x, SO_x) is avoided; (2) the product gas is not contaminated; and (3) the calorific value of the fuel is upgraded. The solar route avoids energy consumption and pollution associated with conventional hydrogen and carbon black (CB) production.

<u>Objectives:</u> The project aims at designing, constructing, and testing innovative solar reactors at various scales (10 kW_{th} and 50 kW_{th}) operating between 1500 and 2000 K. There are three main scientific and technical challenges: 1) design and operation of high-temperature solar chemical reactors containing nano-size particulates; 2) co-production of hydrogen and carbon black (CB) as a high-value nano-material in the same reactor; 3) solar reactor scale-up based on modeling and experimental validation.

<u>Achievements in 2007:</u> A 10-kW_{th} solar reactor prototype based on the indirect heating concept was designed and constructed by CNRS-PROMES (Ref. [4.4]). The solar reactor configuration is depicted in Figure 4.3. The reactor features a 20-cm-side cubic cavity receiver which absorbs concentrated solar irradiation



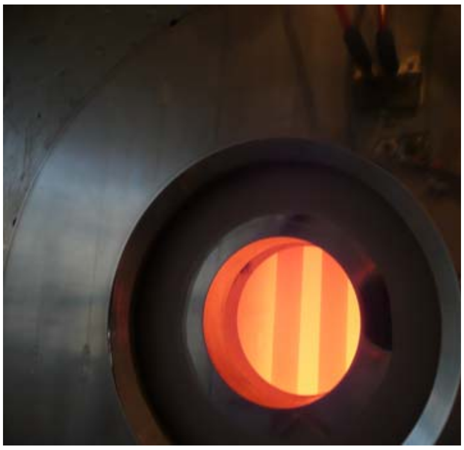


Figure 4.3 Left: Experimental set-up mounted at CNRS solar furnace. Right: Reaction tubes during solar reactor cooling.

through a quartz window. The reaction zones consist of four graphite tubes inserted vertically in the cavity. The reagent gas mixture ($Ar+CH_4$) flows inside each tube and dissociates at high temperature. The reacting flow is separated from the zone receiving the solar irradiation, so particles cannot be deposited on the window.

The solar reactor is currently being tested in experiments at the Solar Furnace in Odeillo, France (Figure 4.3). Gas composition at the reactor outlet, the chemical conversion of CH_4 to H_2, and reactor thermal efficiency are determined for reaction temperature, gas flow rates, and feed-gas composition. Chemical conversion over 90% was measured during the first 1800 K tests, injecting 4 L_N/min of CH_4 (20% in the feed gas).

The solar reactor was modeled by means of a two-phase flow formulation that couples radiative, convective, and conductive heat transfer modes to the chemical kinetics. Simulations were performed to predict reactor performance including temperature distribution, species concentration profiles, and conversion rate of methane at the reactor outlet.

Publication: [4.4]

SYNPET – Hydrogen Production by Steam-Gasification of Petcoke and Vacuum Residue

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

Contacts: Manuel Romero, manuel.romero@ciemat.es
Juan Carlos de Jesus, dejesusjc@pdvsa.com
Aldo Steinfeld, aldo.steinfeld@eth.ch

Funding: PDVSA-CIEMAT-ETH: $ 6,700,000

Duration: January 1, 2003 - December 31, 2008

Background: Hybrid solar/fossil endothermic processes make use of fossil fuels as the chemical source for H_2 production and of concentrated solar energy exclusively as the source of high-temperature process heat. PDVSA, CIEMAT and ETH started a joint project for the development and testing of a 500-kW_{th} solar reactor for steam gasification. In a first phase, after in-depth thermodynamic and kinetic studies, a small 5- kW_{th} prototype was tested in the PSI Solar Furnace. The engineering design, experimentation, and modeling of the solar reactor were presented in Ref. [4.5]-[4.6]. The design, construction, and operation of a 500-kW_{th} reactor are planned for Phase 2 (Ref. [4.7]). Construction is managed by CIEMAT, and it will be operated on the CRS tower at the Plataforma Solar de Almería in 2008.

Objective: The purpose of the project is experimental demonstration of the technology in a 500-kW_{th} solar reactor using solid heavy crude oil derivatives, such as petcoke.

Achievements in 2007: The solar receiver designed by ETH was manufactured at the beginning of 2007. The remaining components, including pneumatic coke transport, heat exchanger,

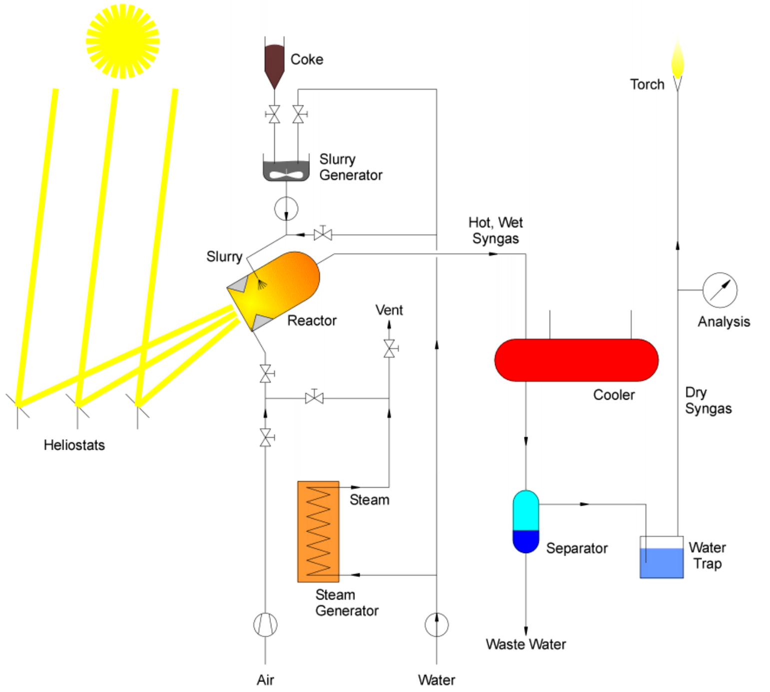


Figure 4.4 Diagram of solar chemical reactor configuration and experimental setup for steam gasification of petroleum coke at the Plataforma Solar de Almería.

torch, etc., for upstream and downstream systems were defined by CIEMAT. A certification procedure following the ATEX 1999/92/EC Directive, which dictates the type of equipment that can be installed in a hazardous area, was followed in view of further commercialization of this technology. In this phase, one of the most important decisions taken by CIEMAT and its partners was to design and construct a large window for the solar reactor. Erection on top of the SSPS/CRS tower at the Plataforma Solar de Almería is expected to be complete by the beginning of 2008. A schematic diagram of the system is shown in Figure 4.4. The suitability of the design for solar coke gasification will be determined after 3 to 6 months' testing. For this plant, between 30-50 kg/h of petcoke consumption for syngas production of around 100-180 Nm^3/h has been estimated.

Exploratory testing included combined pyrolysis and steam-gasification of petroleum vacuum residue. A 5-kW_{th} aerosol-flow solar chemical reactor was tested at PSI's high-flux solar furnace in the 1420-1567 K temperature range (Figure 4.5, Ref. [4.8]). The feedstock was continuously injected as a liquid spray at 423 K into the reactor cavity along with a coaxial steam flow at a H_2O/C molar ratio in the 1.1-7.2 range, and directly exposed to concentrated solar radiation at concentration ratios exceeding 1800 suns. Chemical conversion after a single 1-second residence time pass through was 50% at 1472 K, producing a high-quality syngas composition of 68% H_2, 15% CO, 14% CO_2, and 2% CH_4. The process performance indicators, carbon conversion and energy efficiency, were generally inferior to those for the

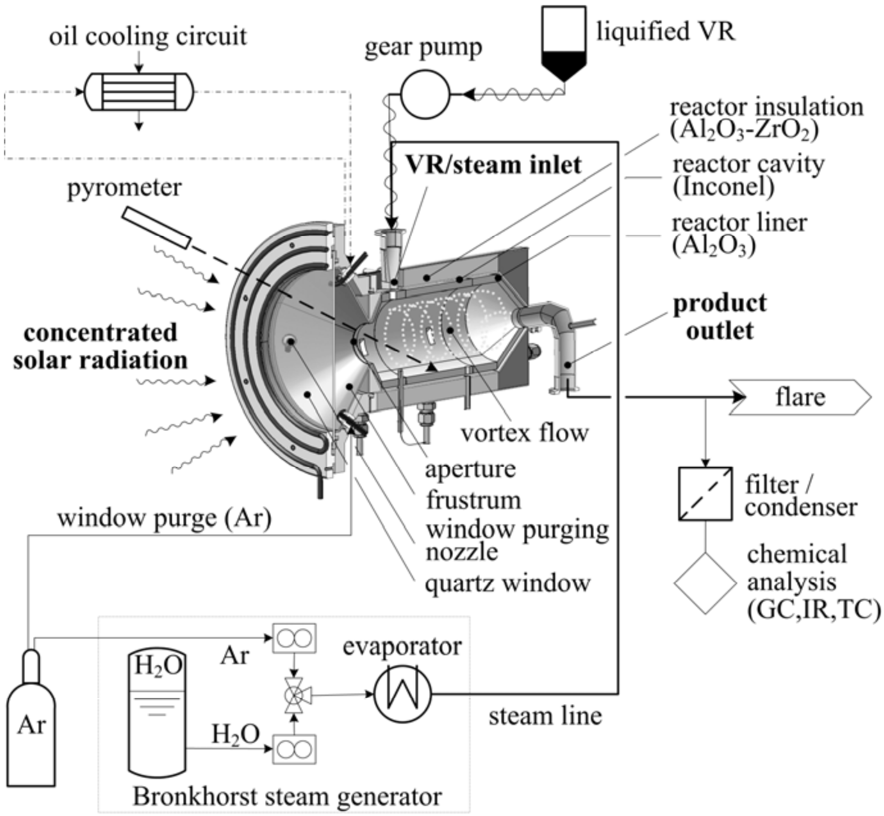


Figure 4.5 *Schematic diagram of solar chemical reactor configuration and experimental setup for the steam-gasification of petroleum vacuum residue (VR), featuring a continuous gas-particle vortex flow confined to a cavity receiver and directly exposed to concentrated solar radiation. Ref. [4.8].*

solar steam-gasification of petcoke under comparable operating conditions.

Publications: [4.5]-[4.8]

IPHE – International Partnership for a Hydrogen Economy Solar-thermal Water Splitting Project

Participants: DLR (D), WIS (IL), CNRS (F), CIEMAT (E), ETH/PSI (CH), Niigata University (J), University of Colorado (USA), General Atomics (USA), UNLV (USA), SNL (USA), NREL (USA)

Contact: Alan W. Weimer, alan.weimer@colorado.edu

Funding: None

Duration: Continuing

Background: Researchers from seven countries, at their primary solar-thermal research laboratories, are working together under the umbrella of this IPHE Project (Ref. [4.9]) to make their efforts more synergistic and less duplicative, and make greater, more rapid progress (Figure 4.6).

Objectives: The project objective is to research, develop and demonstrate cost-effective solar-driven high temperature thermochemical-cycle hydrogen production processes:

- Study the most promising thermochemical cycles, down-select from one to three cycles for development, and fully develop the complete cycle(s) for demonstration.
- Study and develop an improved, lower-cost solar concentrating technology suitable for cost-effective hydrogen production.
- Study and develop solar receiver and thermochemical reactor technology suitable for the selected thermochemical cycle(s).

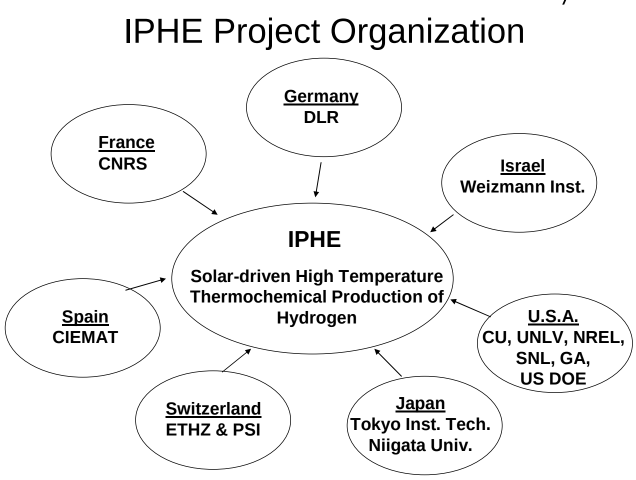


Figure 4.6 IPHE project organization.

Design and demonstrate one to three fully integrated on-sun processes (0.5 – 2 MW power).

Achievements in 2007: The team met and reviewed progress in all the groups at the ASME Sustainable Energy Conference in Long Beach, CA in June. In November, DLR and ETH/PSI attended the U.S. STCH project review, where progress was also shared. A major accomplishment is the finalization of an International Agreement that is being signed by entities in all seven countries. This agreement will allow proprietary aspects of research projects to be discussed so that international collaboration can be improved.

Publication: [4.9]

STCH – Solar-Powered Thermochemical Production of Hydrogen from Water

Participants: University of Nevada Las Vegas (UNLV), University of Colorado (CU), Sandia National Laboratories (SNL), National Renewable Energy Laboratory (NREL), Argonne National Laboratory (ANL), General Atomics (GA), Swiss Federal Institute of Technology (ETH Zurich, CH)

Contact: Alan W. Weimer, alan.weimer@colorado.edu

Funding: U.S. DOE funded project, cost shared: $13,005,000

Duration: June 25, 2003 - December 31, 2007, continuing

Background: Hundreds of thermochemical cycles to split water have been proposed. The feasibility of these processes can be assessed through thermodynamic analysis and experimentation. There is a need to evaluate these cycles in order to identify the most feasible and economical for further investigation. The most promising cycles should be demonstrated.

Objectives: The main objective of the STCH project is to identify a cost-competitive solar-powered water splitting process for hydrogen production. Up to three processes will be demonstrated, including on-sun experimentation.

Achievements in 2007: Five cycles are currently under active study by STCH. These include: (1) zinc oxide and cadmium oxide volatile metal oxide cycles, (2) sodium manganese and cobalt ferrite non-volatile metal oxide cycles, and (3) hybrid copper chloride cycle. In addition, a solid-particle receiver is being constructed to interface to hybrid sulfur and SI cycles.

Zinc Oxide – Carefully designed experiments were performed to determine the rates of thermal ZnO dissociation and Zn hydrolysis. Thermogravimetric experiments were used to establish a rate law for each reaction; aerosol experiments tested the applied model in an environment where diffusion controls were relatively unimportant (Ref. [4.10]). CFD simulations were performed with the commercial finite element code COMSOL Multiphysics. The simulations incorporated the kinetic models found from experimentation as well as a participating media approach for radiation heat transfer to the particulate phase.

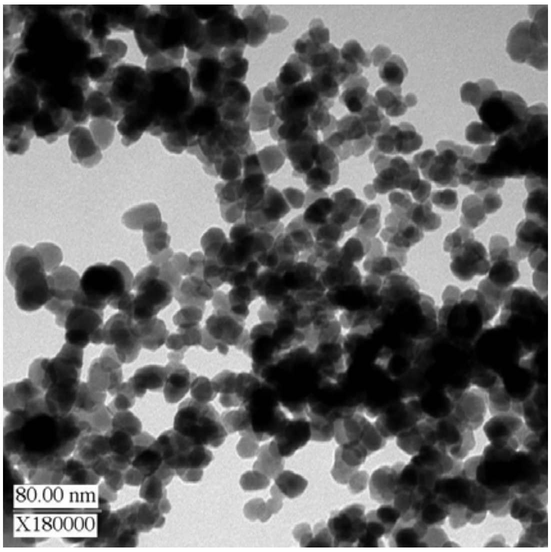


Figure 4.7 Transmission electron micrograph (TEM) of Zn particles collected from aerosol reactor operating at 1750ºC (180,000x).

ZnO dissociation was shown to follow a L'vov-style rate model, which includes Arrhenius temperature dependence coupled with rate control by diffusion away from the reacting surface. The activation energy for this reaction was 356±25.9 kJ mol^{-1}; the pre-exponential factor depended on diffusion resistance for transport away from the particle surface. This led to the prediction that reaction in a dispersed aerosol reactor would be much faster than in a stationary (e.g. thermogravimetric analyzer) configuration. This was borne out by experiment, where aerosol rates were three orders of magnitude greater than in the stationary cases. The aerosol reactor configuration generated extremely small particles (10-50 nm) due to limited opportunity for growth during quenching (Figure 4.7).

Cadmium Oxide – Hydrolysis of solid cadmium requires continuous refreshment of clean metal surface because of the formation of a passivating hydroxide layer. A combination of milling and use of carbon dioxide for chemical removal of the hydroxide layer was found effective. The CO_2 generates a porous cadmium carbonate interface, exposing underlying fresh cadmium for hydrolysis. Cadmium carbonate crystals were found to break off the surface as the layer grows. Hydrolysis of molten cadmium was accomplished by passing a steam-saturated carrier gas through the melt. Results to date show a steady state conversion efficiency of water vapor passing through the melt to hydrogen between 15% and 20% but it is anticipated that the rate will improve upon maximizing the contact area between the metal and steam. Present results show that the cadmium oxide particles formed by the molten hydrolysis process are about 0.5 µm in diameter. Preliminary TGA tests show that the CdO decomposition reaction completion temperature varies from 1300°C in air to 1640°C in oxygen (Figure 4.8).

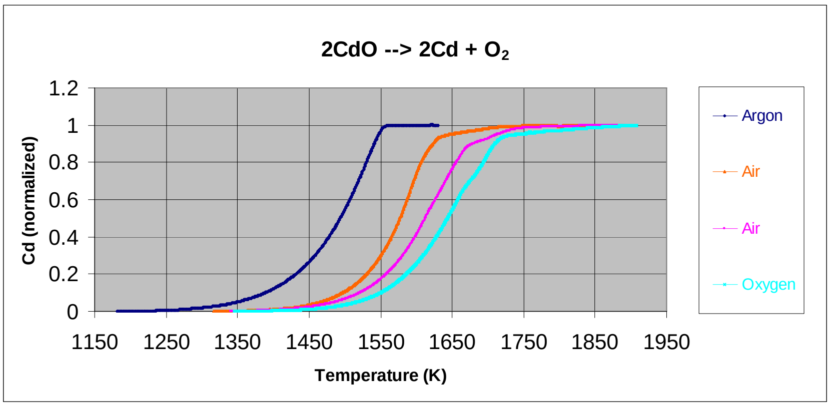


Figure 4.8 Decomposition of cadmium oxide in different gas environments.

Copper Chloride – A preliminary process flow diagram for the Cu-Cl cycle was prepared using Aspen Plus with data from a completed proof-of-principle experiment for the two thermal reactions. The decomposition of Cu_2OCl_2 was shown in the laboratory to be a simple thermal decomposition. A mechanism was hypothesized and kinetic data has been obtained.

Work is currently focused on understanding the hydrolysis reaction. Sensitivity analyses of the model showed a critical need for accurate thermodynamic data for Cu_2OCl_2, which were subsequently measured and added to the physical properties database. The updated model predicted that the presence of HCl in the steam stream in the hydrolysis reaction could inhibit the formation of Cu_2OCl_2. Engineering methods to minimize HCl content were determined. Thermodynamics predicted 98% yield of Cu_2OCl_2 at 375°C with no significant formation of CuCl when using a steam-to-copper molar ration of 17:1. Experiments showed about 85% yield with significant CuCl formation.

Proof-of-principle experiments for the electrochemical reactions showed hydrogen production. AECL designed and tested a flow-through electrochemical cell using various membrane and electrode materials in the 3-reaction model that avoids the necessity of Cu formation from CuCl in the 4-reaction option.

Ferrites – Ferrite feasibility tests were conducted using cobalt ferrite ($Co_{0.67}Fe_{2\,0.33}O_4$) supported on yttria-stabilized zirconia in a 1:4 ratio by weight. The samples were cast as three dimensional lattice structures and tested on-sun. Hydrogen production with these materials involves two chemical reactions: (1) a high temperature (1550°C) thermal reduction to produce oxygen followed by (2) a lower temperature (1100°C) water oxidation to produce hydrogen. The cobalt ferrite material was run for 10 consecutive cycles with no noticeable loss in chemical performance or structural integrity. In fact, the hydrogen yield increased with the number of cycles. These results are promising in that these materials must maintain reactivity and structural integrity over thousands of cycles in a practical device. A dataset from the on-sun testing is shown in Figure 4.9. A completed prototype will be used for on-sun testing at a power level of near 9 kW_{th}.

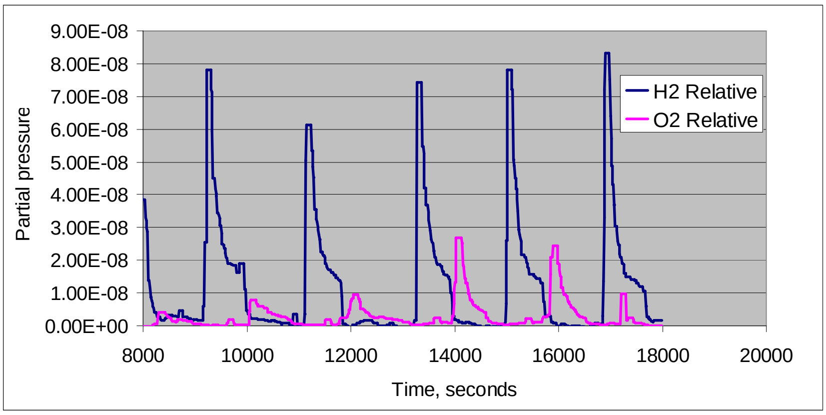


Figure 4.9 Hydrogen production during on-sun testing of cobalt ferrite ($Co_{0.67}Fe_{2\ 0.33}O_4$: YSZ – 1:4 by weight). Oxygen production at 1500°C, hydrogen production at 1100°C.

Solid Particle Receiver – The solid particle receiver is a direct absorption receiver in which solar energy heats a curtain of falling ceramic particles to a temperature in excess of 1000°C (Ref. [4.11]-[4.12]). A small-scale test platform was built to investigate particle flow properties. Tests were conducted to experimentally determine the distribution of velocity, curtain thickness, and curtain opacity along a drop length of approximately 3 m. Velocity data were measured using a high-speed digital camera to image the particle flow at 1000 frames per second with an exposure time of 100 microseconds. Five mass flow rates ranging from 1 kg s^{-1} m^{-1} to 22 kg s^{-1} m^{-1} were tested, and it was found that all flows approached a terminal velocity of about 6-7 m s^{-1} in a 3-m drop.

Curtain opacity was measured by taking backlit images of the flow from the front. The opacity was determined by calculating the ratio of the area covered by particles to the total frontal area of the images. In general, the flow is fairly opaque just downstream of the discharge point and then becomes progressively more diffuse as it drops. Eventually the opacity ranges from 0.65 at discharge to 0.45 at terminal velocity. Opacity increases with mass flow rate.

Construction of the on-sun receiver is nearing completion. Testing will be at the 1-2-MW level in batch mode. The particle inventory is sufficient to allow batch tests in excess of five minutes.

Publications: [4.10]-[4.12]

Hydrogen Production from Solar Thermochemical Water-Splitting Cycles

Participants: CNRS-PROMES (F), CEA/DEN/DTCD/SCDV-LPIC (F)

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Stéphane Abanades, abanades@promes.cnrs.fr

Funding: CNRS

Background: The most promising solar-driven thermochemical cycles are generally based on metal oxide redox pairs. In addition to the hydrogen generation step (water-splitting), the metal oxide cycles always involve an endothermic reduction reaction in the first step which must be carried out in a high-temperature solar reactor. This solar step requires the development and performance assessment of solar reactor concepts suitable for metal oxide processing.

Objectives: The objectives of this study are the selection and experimental evaluation of promising multi-step cycles for hydrogen production. Reactor engineering and energy efficiency analysis of solar processes complete the research.

Achievements in 2007: Three-step metal oxide cycles were experimentally studied for determining operating conditions, chemical conversions and kinetic rates. The cycles based on iron oxides produced hydrogen as opposed to cobalt and manganese oxides. The three-step cycle involving the Fe_2O_3/Fe_3O_4 redox pair was studied (Ref. [4.13]). Magnetite was prepared easily with concentrated solar energy under air at 1300°C. NaOH activation reaction reached a chemical conversion higher than 70% after 7 minutes at 400°C, and final conversion was not dependent on particle size. Reaction was complete when KOH was employed. Moreover, the hydrolysis of the mixed oxide synthesized in the reaction with NaOH was complete for a temperature of 100°C, which closed the cycle. Advantages of this cycle are its rapid kinetics, high chemical conversion, no grinding, and lower reduction temperature than for wustite (1300°C under air for Fe_3O_4 instead of 1600°C under inert atmosphere for FeO). Similarly, 3-step cycles based on reduced mixed compounds were also demonstrated. The high temperature synthesis of reduced cerium-based mixed oxides ($Ce_2Ti_2O_7$, $CeFeO_3$, $CeVO_4$, and $CeNbO_4$) was performed in a lab-scale solar reactor at below 1400°C. The activation reaction with NaOH or KOH produced up to 1.74 mmol H_2/g in the range 500-600°C.

A laboratory-scale solar reactor (Figure 4.10) was designed and simulated for the thermal reduction of metal oxides involved in thermochemical cycles (Ref. [4.14]). This reactor features a rotating cavity-receiver, in which solid particles are continuously injected. It can operate under controlled atmosphere. A computational model was developed at reactor scale by coupling the fluid flow, heat and mass transfer, and the chemical reaction. The reactive particle-laden flow was simulated, based on a discrete phase model (Lagrangian approach). The kinetics of the chemical reaction was considered in the specific case of zinc oxide dissociation, because reliable data on the ZnO dissociation reaction are available. The simulation yielded trends about the reactor thermal behavior and the reaction extent. For example, completion of the reaction was predicted for particle temperatures exceeding 2200 K for a 1 μm initial

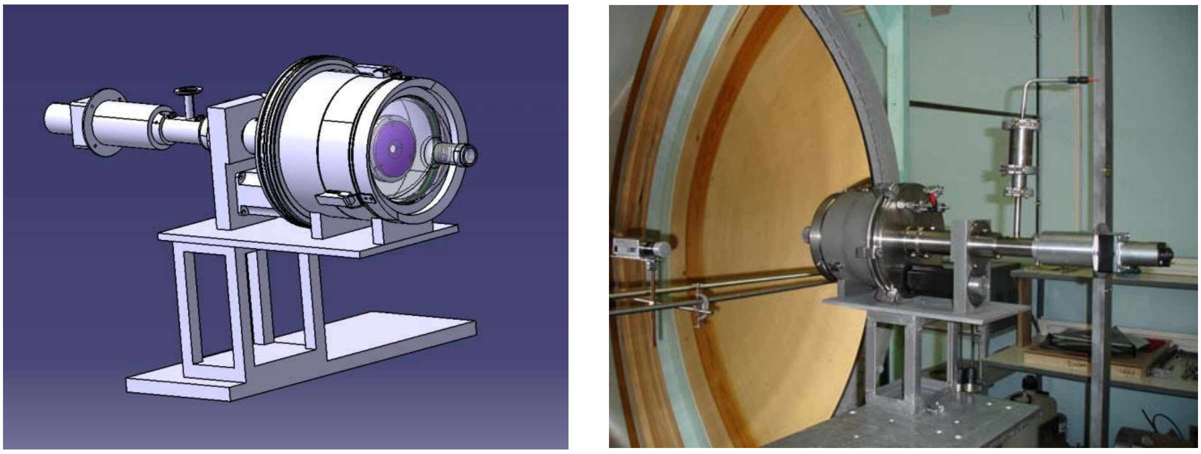

Figure 4.10 CNRS rotating solar reactor for continuous metal oxide processing. Left: schematic front view; right: picture of lab-scale reactor looking towards parabolic mirror concentrator.

particle diameter.

Publications: [4.13]-[4.14]

Solar Hydrogen Production from a ZnO/Zn Thermochemical Cycle

Participants: PSI (CH), ETH (CH)

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Christian Wieckert, Christian.wieckert@psi.ch
Aldo Steinfeld, aldo.steinfeld@eth.ch

Funding: BFE-Swiss Federal Office of Energy, PSI, ETH

Duration: January 1, 2003 - December, 2007

Background: The production of hydrogen from water using solar energy in a two-step 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 hydrolysis of Zn at 700 K to form H_2 and ZnO(s). The latter separates naturally and is recycled to the first step. H_2 and O_2 are derived in different steps, thereby eliminating the need for high-temperature gas separation.

<u>Objectives</u>: 1) Solar chemical reactor technology for the production of Zn by thermal dissociation of ZnO; 2) solar chemical reactor modeling using CFD and Monte Carlo ray-tracing simulations; 3) fundamental research on the re-oxidation and quenching of Zn(g); 4) production of H_2 by hydrolysis of Zn.

<u>Achievements in 2007</u>: The 2nd step of the ZnO/Zn cycle has been experimentally demonstrated using an aerosol-flow reactor for in-situ formation and hydrolysis of Zn nanoparticles (Ref. [4.15]). For the 1st solar step, the proposed chemical reactor concept is based on a rotating cavity-receiver lined with ZnO particles that are held by centrifugal force and directly exposed to high-flux irradiation. With this arrangement, ZnO serves simultaneously as radiant absorber, chemical reactant, and thermal insulator.

A schematic of the 10 kW_{th} solar reactor configuration is shown in Figure 4.11. Its main component is a 160 mm-diameter

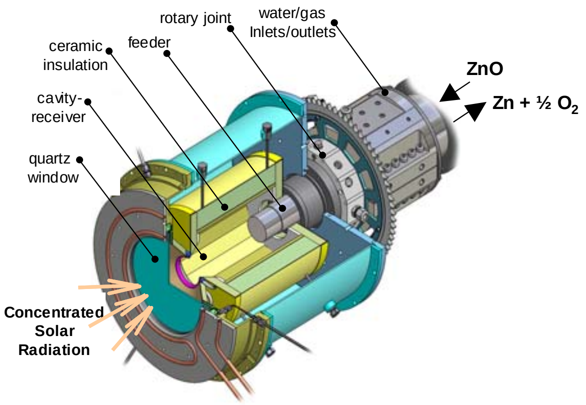

Figure 4.11 Schematic of the solar chemical reactor configuration.

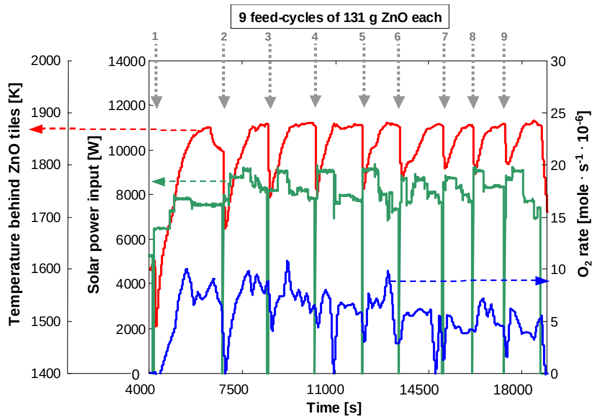

Figure 4.12 Radiative power input, cavity temperature, and O_2 molar flow rate measured during a solar run with 9 feed cycles of 131 g ZnO each. Ref. [4.17].

rotating cylindrical cavity composed of sintered ZnO tiles on top of multi-layer Al_2O_3-SiO_2-Y_2O_3-based ceramics for thermal shock resistance, mechanical stability, gas diffusion barrier, and thermal insulation. Concentrated solar radiation enters the cavity through a 60 mm-diameter windowed aperture. The reactor has a dynamic feeder that extends and contracts within the cavity, and enables to evenly spread out a layer of ZnO particles that are held by centrifugal force. Inert gas (Ar) is injected through nozzles located around the aperture, creating an aerodynamic curtain (designed by CFD) that protects the window from condensable Zn(g). Gaseous products Zn(g) and O_2 exit the cavity through a water-cooled annular gap, referred to as the "quench unit".

Experimentation was carried out at PSI's High Flux Solar Simulator (HFSS, Ref. [4.16]). The radiative power input through the reactor's aperture was in the range of 1.6-9.9 kW, with a peak solar concentration ratio of 5880 suns (1 sun = 1 kW/m^2). Figure 4.12 shows the power input, cavity temperature (behind the ZnO tiles), and O_2 flow rate in the product gases measured during a 4-hr experimental run with 9 feed cycles of 131 g of ZnO each (Ref. [4.17]). To avoid overheating of the feeder, the power input was interrupted briefly (~50 s) during each feeding cycle. The reactor was operated in "ablation" mode, where the rate of heat transfer – predominantly by radiation – to the thin layer of ZnO particles undergoing endothermic dissociation proceeds faster than the rate of heat transfer – predominantly by conduction – through the cavity walls.

Rapid cooling to avoid the recombination of Zn(g) and O_2 derived from the solar thermal dissociation of ZnO was investigated using online thermogravimetry coupled to a three-zone quenching unit, as shown in Figure 4.13: 1) in an inlet hot zone at the solar reactor outlet, the wall temperature is kept above the ZnO decomposition temperature; 2) in the transition zone above the Zn(g) saturation temperature, annular Ar flow (AF) diminishes Zn(g)/O_2 diffusion to the walls; and 3) a cold outlet zone with water-cooled walls and injection of Ar quench gas (QF) sharply decreases temperatures and slows down oxidation kinetics. Measured cooling rates ranged from 20,000 to 120,000 K/s. Zinc content of the collected particles downstream varied in the 40-94% range for Ar/Zn(g) dilutions of 170 to 1,500 (Ref. [4.18]).

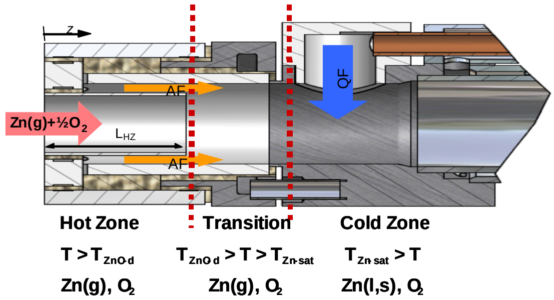

Figure 4.13 Schematic of the quenching unit illustrating the three temperature zones (AF: annular flow; QF: quench flow). Ref.[4.4]

Publications: [4.15]-[4.18]

HYDROSOL-2 – Solar Hydrogen via Water Splitting in Advanced Monolithic Reactors for Future Solar Power Plants

Participants: CERTH/CPERI (GR), DLR (D), Stobbe Tech (DK), Johnson Matthey Fuel Cell Ltd. (UK), CIEMAT (E)

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

Funding: EC (FP6), DLR

Duration: November 1, 2005 - October 31, 2009

Background: A promising new method for solar-heated two-step water-splitting thermochemical processes operating at temperatures below 1500 K is being developed. It includes a support structure able to achieve 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 feasibility of this technology was previously demonstrated in the HYDROSOL project. A pilot-scale solar reactor for continuous production of "solar hydrogen", was designed, built and operated at the DLR solar furnace facility in Cologne (Germany), (Ref. [4.19]).

Objectives: 1) Based on the novel reactor concept, develop and test an optimized pilot plant (100 kW_{th}) at the Plataforma Solar de Almería (PSA, Spain); 2) further scale up this technology and demonstrate its effective coupling with solar concentrating systems; 3) provide stable metal oxide/ceramic support assemblies able to perform at least 50 water-splitting cycles in a row; 4) decrease the temperature of the regeneration step to considerably less than 1500 K; 5) optimize the water-splitting and oxygen-release efficiency; 6) develop the solar field control strategy.

Achievements in 2007: The results of the project can be summarized as follows:

- The hydrogen production performance of iron-oxide based materials has been improved by applying aerosol spray pyrolysis in their preparation.
- Coating techniques have been optimized with respect to both their stability and large-scale coating of porous ceramic honeycomb supports required for the field-test operation of a pilot reactor at the Plataforma Solar de Almería (PSA).
- After successful demonstration of over 50 hydrogen generation and metal oxide reduction cycles in a row on one sample, further experiments were carried out at DLR's solar furnace in May/June 2007. This campaign confirmed the earlier findings that the coating/support assembly is stable enough for use in the pilot plant. Parametric studies revealed impacts of the main process parameters such as temperatures, cycle duration and partial pressures on the performance of the cyclic process. A modular two-chamber solar reactor was employed as a model for the planned pilot reactor and for elaborating the pilot plant operating strategy (Ref. [4.20]). In the solar furnace, control of the incoming concentrated solar radiation was provided for each individual reactor module using a lamellae shutter, while in a solar tower configuration the heliostats will be grouped and alternately readjusted (Figure 4.14).

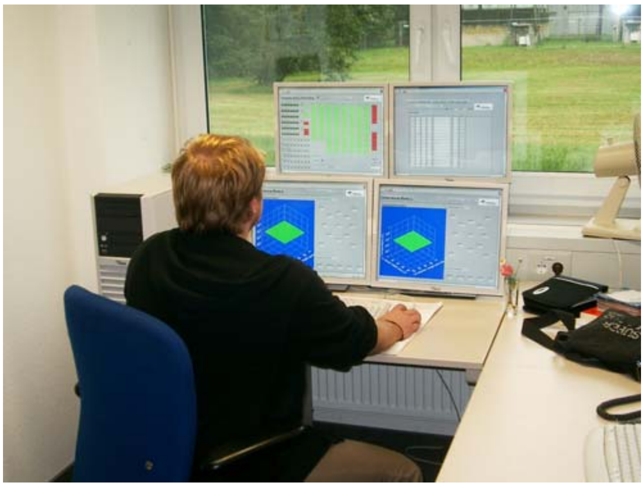

Figure 4.14 Testing the 100 kW_{th} dual chamber pilot reactor unit control program.

- Experiments in the solar furnace helped define the appropriate process parameters for the scaled-up solar chemical plant at the PSA. Step-response experiments facilitated determination of the transient behavior of the hardware and completion of a control procedure.

- Peripheral systems for the 100 kW_{th} pilot plant have been installed and tested on the solar tower platform. The receiver-reactor is under construction and will be integrated and installed at the SSPS tower of PSA early in 2008. First experimental tests are scheduled for shortly after completion of installation.

Publications: [4.19]-[4.20]

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

Participants: CEA (F), DLR (D), University of Sheffield (UK), Università degli Studi – Roma Tre (I), Empresarios Agrupados (E), ProSim SA (F)

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

Funding: EC (FP6), DLR

Duration: April 1, 2004 - December 31, 2007

Background: Among the most promising processes for massive hydrogen production (other than electrolysis) are thermochemical cycles using water as the raw material and process heat from either concentrated solar energy or nuclear power plants. This project focuses on two sulfur family processes, the Westinghouse (WH) and Sulfur-Iodine (S-I) processes. The WH process is a hybrid electrochemical/thermochemical cycle for decomposing H_2O into H_2 and O_2 with the use of SO_2 which is then converted into H_2SO_4 and SO_3 as an intermediate stage. The S-I process makes use of SO_2 and I_2 which are converted to H_2SO_4 and HI.

Objectives: 1) Develop solar-heated sulfur-based thermochemical processes for the production of hydrogen; 2) perform a comparative assessment of solar, nuclear, and hybrid heated S-I and WH thermochemical cycles; 3) improve chemical processing and efficiency of both processes.

Achievements in 2007: The major achievements of the HYTHEC project are summarized in Ref. [4.21].

Sulfur-Iodine (S-I) Cycle:

- Completion of overall analysis of the sulfur iodine cycle, based on reference flow-sheet, major component sizing and costs, and overall cycle economic evaluation.
- Successful application of a methodology for studying the liquid-vapor equilibrium over ternary HI-H_2O-I_2 mixtures and of optical analytical techniques to characterize the speciation of the vapor phase of the HI_x section of the sulfur iodine cycle.
- Significant potential for improvement of process conditions has been identified by experiments and process simulation. Feed dewatering leads to a significant gain in the overall process efficiency.

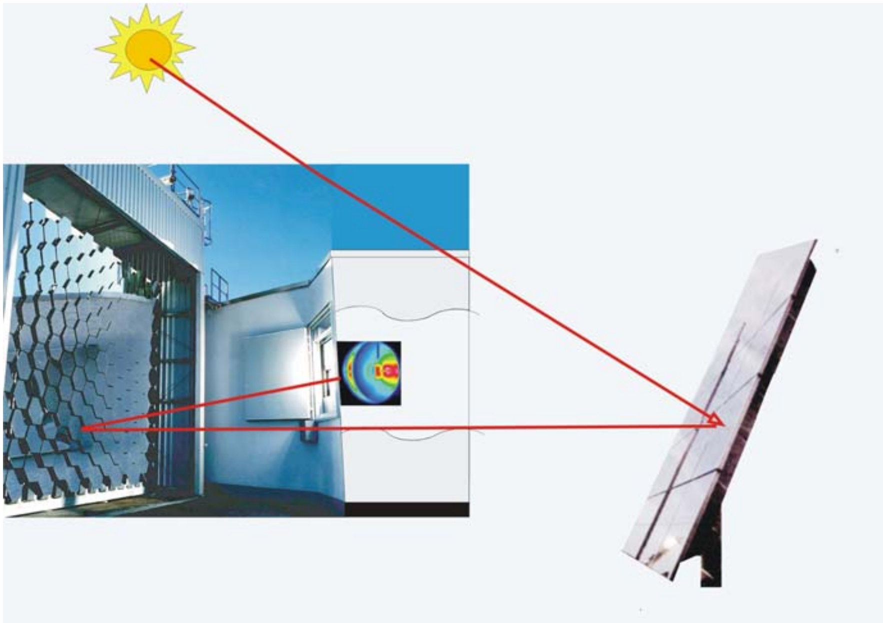

Figure 4.15 Sketch of DLR Solar Furnace experiment for testing the sulphuric acid decomposition reactor.

- Feasibility and successful testing of solar H_2SO_4 splitting in a solar receiver-reactor (Figure 4.15): H_2SO_4 decomposition was carried out with over 90% yields using platinum-coated honeycomb absorbers. Up to 40% reactor efficiencies were reached with average absorber temperature kept well below 1000°C.
- A model of the receiver-reactor has been developed and validated by experimental data, which can predict the most promising processing conditions, the behavior of the reactor under steady-state and transient conditions, and the performance of a scaled version on a solar tower.

Westinghouse (WH) Cycle:

- Flow-sheets were completed for solar-only and solar-nuclear hybrid plants for the hybrid sulfur cycle (Westinghouse cycle). Solar power installed is roughly three times the annual average. For the solar-only case, a 140 MW_{th} plant appears to be close to the cost optimum.
- For two scenarios, the components of both the solar and chemical plant sections have been sized. Predicted hydrogen production costs are around 5€/kg with potential reduction to less than 3€/kg.
- For small plant sizes (50 MW_{th} on average), solar-only plants are economically advantageous, while for large-scale production (over 500 MW_{th}) nuclear-heated plants lead to the most economic results. In the intermediate power range, hybrid plants have the lowest hydrogen production costs.

Publication: [4.21]

SOLTERH – Solar Thermochemical Production of Hydrogen by Water-Splitting Processes

Participants: Solúcar Energía S.A. (E), Hynergreen Technologies S.A. (E), CIEMAT-PSA (E)

Contacts: Alfonso Vidal, alfonso.vidal@ciemat.es

Funding: Spanish Ministry of Science and Education (PROFIT): €770,000

Duration: January 1, 2004 - December 31, 2008

Background: Thermochemical cycles are expected to be a cost and energy-efficient way to produce large amounts of hydrogen. Two-step water splitting processes, such as ferrites, are very attractive candidates since there is no phase transformation during the redox cycle. A study to identify critical factors for developing this technology has been initiated at the CIEMAT. For example, the choice of directly-irradiated volumetric receivers versus cavity receivers for solar catalytic reactions is still a key decision in technology development. This project seeks to solve the technical problems encountered in cavity receivers for solar heterogeneous reactions.

Objective: The project aims at designing, constructing, and testing innovative solar particle receiver-reactors at different scales (1 to 5 kW_{th}) at operating conditions of about 800-1200°C.

Achievements in 2007: Detailed Computational Fluid Dynamics (CFD) simulation of various flow patterns in the reactors under development is underway. For simplicity, a cylindrical geometry was chosen for the outline of the reaction chamber used in the simulation. For model validation, some exploratory tests were conducted at the laboratory using a reactor vessel equipped with a windowed aperture for viewing the fluid flow. The chamber is provided with electrical heating, and a set of inlets enables different flow configurations. A steam and particle slurry is injected into the reactor cavity. Experimental observation of a solid particle deposit seems to be in agreement with CFD modeling results. CFD simulations, supported by viewing the actual flow, indicate that some reactor configurations offer a stable flow with minimum mixing (Figure 4.16). CFD is therefore becoming an important tool in the development an effective solar reactor.

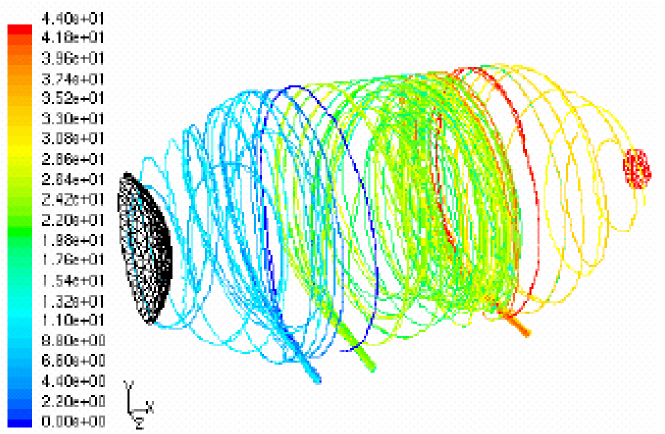

Figure 4.16 Simulation of path lines in a cylindrical cavity reactor.

PHYSICO2 – Clean Hydrogen Production by Carbon Dioxide Free Alternatives

Participants: University Rey Juan Carlos I Madrid (E), ICP-CSIC (E), CIEMAT (E), REPSOL-YPF (E), Hynergreen Technologies S.A. (E)

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Funding: The Community of Madrid: €2,017,000

Duration: January 1, 2006 - December 31, 2009

Background: The PHISICO2 project (Clean production of hydrogen: CO_2 emission-free alternatives) progresses in solving current technological and economic limitations by exploring different processes for clean hydrogen production, essential to future transition towards a hydrogen economy (Ref. [4.22]). The alternatives in this project feature prevention of CO_2 as a hydrogen by-product by using renewable energy sources to power its generation. The research in this project considers hydrogen production 1) from decomposition of natural gas assisted by heterogeneous catalysts; 2) by water photo-dissociation; 3) from water through solar-thermal processes based on thermochemical cycles.

Objective: Evaluation and optimization of three different processes for clean, carbon dioxide-free emission hydrogen production.

Achievements in 2007: Rey Juan Carlos University foresees the preparation of new catalysts based on highly active, durable carbonaceous materials for natural gas decarbonization. The use of carbon as a catalyst has the advantage, among others, of not requiring regeneration after on-stream operation. Ferrites metal-doped with $M_{0.25}Mn_{0.75}Fe_2O_4$ (M: Mn, Co, Ni, Cu) have been studied by the CIEMAT (Ref. [4.23]). Activated ferrites lead, however, to lower hydrogen production than expected from the water-splitting stoichiometry. Of the materials studied, $Ni_{0.25}Mn_{0.75}Fe_2O_4$ leads to the highest hydrogen evolution per gram of sample, and is also the closest to stoichiometric H_2 production. Metal oxides such as MO_x, or mixed oxides $M_xM'_yO_z$, in which M and/or M' have a d10 electron configuration (Ga^{3+}, In^{3+}, Pb^{4+} and Sn^{4+}), have been synthesized and tested by ICP-CSIC (Ref. [4.24]). Semiconductors exhibiting certain amount of activity will be promoted with minor amounts of NiO or Pt to improve water-splitting efficiency, which is a key parameter for possible commercial application of these processes.

Publications: [4.22]-[4.24]

Solar Hydrogen Production with Quantum Boost

Participants: Science Applications International Corp. (SAIC), Florida Solar Energy Center (University of Central Florida), U.S. Department of Energy, Golden Office (DOE)

Contacts: Robin W. Taylor, taylorro@saic.com

Funding: $3,999,000

Duration: June 13, 2007 - February 28, 2009

Background: The goal of this project is to develop and demonstrate a solar-driven process for efficient hydrogen production by water-splitting, employing a high-energy photon "quantum boost". The direct use of the photonic energy of sunlight differentiates this approach from other solar hydrogen production schemes that degrade the solar input to thermal energy, and is therefore potentially highly efficient.

Objective: The project includes identification and development of suitable chemical reactions, development of a bench-scale system, and scale-up to a pilot-size solar hydrogen production system with full recycle loops.

Achievements in 2007: The project has only recently begun, but present emphasis is on a sulfur-ammonia photo-/thermochemical cycle represented by the following reactions:

(1) $SO_2 + H_2O + 2NH_3 \rightarrow (NH_4)_2SO_3$
(2) $(NH_4)_2SO_3 + H_2O \rightarrow (NH_4)_2SO_4 + H_2$
(3) $x(NH_4)_2SO_4 + M_2O_x \rightarrow 2xNH_3 + M_2(SO_4)_x + xH_2O$
(4) $M_2(SO_4)_x \rightarrow xSO_2 + 2MO + (x\text{-}1)O_2$

where M is a metal such as Zn, Mg, Ca, Ba, Fe, Co, Ni, Mn, or Cu. Reaction (1) is a simple chemical absorption reaction to form ammonium sulfite. Reaction (2) is a photocatalytic reaction that uses high-energy photons from sunlight to produce ammonium sulfate and release hydrogen. Reactions (3) and (4) are thermocatalytic reactions that take place in a reactor heated by concentrated solar energy. Hydrogen and oxygen are produced in different reactors, eliminating separation steps. The solar spectrum can be split to provide both high-energy photons and thermal energy.

Publications: [4.25]-[4.27]

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PART 5: Status Report Task III: Solar Technology and Advanced Applications

Operating Agent:
Christoph Richter
DLR TT-SF AS (Plataforma Solar de Almería)

5 Task III: Solar Technology and Advanced Applications

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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. This also concerns, among others, process heat applications, the utilization of solar concentration for the development of improved materials, and the introduction of hybrid solar/fossil power plant concepts.

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 2007-2011 Task III Objectives

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.
- **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.
- **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 2007 are summarized in Table 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. List of activities reported in 2007

Topics	Activity / Project short title	Contact	Sharing			
			I	M	T	C
Sector 1. Components and Subsystems						
Central Receiver Systems	Solhyco	P. Heller		x		
	25m2 target-aligned research heliostat	Th. Roos	x			
Parabolic Trough	REAL-Diss	M. Eck, P. Fontela-Martinez (ENDESA)		x		
	Parfor	N. Benz J. Schulte-Fischedick (SCHOTT Solarthermie GmbH)	x			
	DIVA	M. Eck (DLR), N. Benz (SCHOTT Rohrglas)	x			
	Drehflex HCE connection	F. Ortiz-Vives, A. Kaufung (Senior Berghoefer GmbH)	x			
Linear Fresnel	Fresdemo	R. Bernhard (MAN Ferrostaal Power Industry)	x			
	Advanced, High-Temperature Linear Power Tower System	R. C. Gee (Skyfuel)	x			
	Fresquali	W. Platzer (Fraunhofer—ISE)	x			
Storage	ITES	D. Laing (DLR)	x			
Dish	Parabolic Dish Development in Mexico	C. Ramos Berumen (IIE)	x			
	Hybrid Solar Dish/Stirling Power System	R. W. Taylor (SAIC)	x			
	Solar Dish/Photovoltaic Power System	R. W. Taylor (SAIC)	x			
	Big Dish Solar Thermal Concentrators	K. Lovegrove (ANU), A. Zawadski (Wizard Power)	x			
	Ammonia Dissociation Based Solar Energy Storage	K. Lovegrove (ANU), A. Zawadski (Wizard Power)	x			
Sector 2. Supporting Tools and Test Facilities						
Simulation Tools	Water efficient cooling	C. Richter (DLR)			x	
Measurement Systems	Saphir	S. Ulmer (DLR)	x	x		
Sector 3. Advanced Technologies and Applications						
High Temp. Process Heat	SolarPRO II	D. Martinez, CIEMAT	x			
	Thermal Treatment of metallic materials	D. Vazquez, (CENIM-CSIC), I. Cañadas (CIEMAT)	x			

5.3 Summary of Achievements

5.3.1 Sector III.1: Solar Specific Technology, Components and Subsystems

This sector covers general activities and in the fields of

- Central Receiver Systems
- Dish/Stirling Systems
- Linear Collectors (Parabolic Troughs, Fresnel)
- Storage

CENTRAL RECEIVER SYSTEMS

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), FTF (D), NEAL (ALG), FUSP (BRA), Vitalux (BRA), IIE (Mex)

Funding: EC FP6 STREP; 3.4 M€ total cost, duration 42 months

The SOLHYCO project focuses on the development of a prototype solar-hybrid microturbine conversion system for cogeneration with a unit power of 100kW$_e$. Project innovations are:

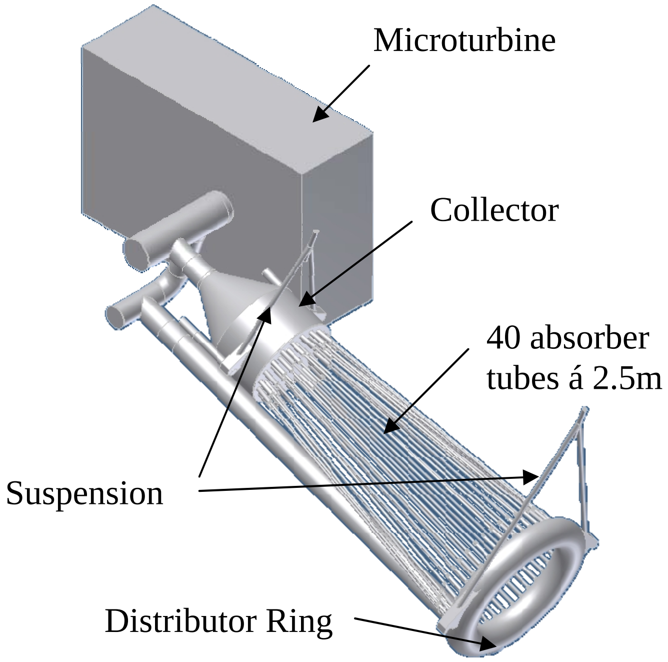

Figure 5.1 Solar receiver design (w/o cavity) for TURBEC micro turbine (100 kWe) for cogen applications

- Development of a solar-hybrid microturbine prototype unit based on a commercial microturbine
- Development of a new receiver based on a new high-performance tube technology
- Development of a combustion system able to operate with biofuels

During the second year of the project, several sample multi-layer absorber tubes were manufactured. Development of the hydro-forming tube manufacturing method is not yet complete.

The solar receiver for the microturbine system was designed (Figure 5.1) and manufacturing will be finished in April 2008. The receiver is built from monolayer high-temperature alloy tubes with optional integration later of multilayer tubes. The design and manufacture of the microturbine system was completed.

The new biofuel combustion system was adapted to the old SOLGATE test bed using the OST3 turbine (250 kW_e) system with the 3 solar receivers. Pre-test with turbine and solar components was almost completed, system testing will start in January 2006 in the CESA-1 solar tower facility at Plataforma Solar de Almeria. Improved mass flow measurements will ensure highly accurate test results.

A first dissemination workshop was held in Brazil. Portuguese and Spanish project web pages were designed.

Literature: www.solhyco.com

25m² target-aligned research heliostat with closed-loop control

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Participants: CSIR

Funding: Internal

Figure 5.2 Rear view of heliostat, showing focal spot on target wall

A 25-m² target-aligned research heliostat with closed-loop control and a theoretical concentration of 80 suns has been built at CSIR in South Africa. The heliostat has four degrees of freedom: Azimuth, Elevation, Rotation and Pitch. Manual Azimuth and Elevation controls set the orientation of the Rotation axis, while Rotation and Pitch are electrically actuated using a control system making use of a solar tracker, dispensing with the need for a solar algorithm. The control system was developed and tested on a 1.25 m² target-aligned mini-heliostat, obtaining a tracking accuracy of 3.3 milliradians. Future work entails developing a calorimeter to characterize the focal spot.

Literature:

LINEAR COLLECTORS (PARABOLIC TROUGHS, FRESNEL)

Parabolic Troughs

REAL-DISS

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Funding: German Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and Corporación Tecnológica de Andalucía

Direct steam generation (DSG) in parabolic troughs has been proven feasible in a full-size test facility. The logical next step is the design, erection and operation of a first demonstration plant. The size of the demonstration plant has to be a scalable fraction of a follow-up commercial DSG solar thermal power plant. The German-Spanish project REAL-DISS aims not only at the development of this demonstration plant, but is also developing all the components required for a commercial DSG plant. Project partners are the German Aerospace Center (DLR), Endesa, MAN Solar Millennium (MSM), Flagsol, SCHOTT, Senior Berghöfer and Milenio Solar Desarrollo de Proyectos.

The main medium-to-long-term target of the project consortium is the design, construction and commercial operation of a 50-MW-capacity DSG solar thermal power plant in Spain. Several steps have to be taken in advance to reduce the risk. Currently, some major components, such as flexible tube connections, storage systems and absorber tubes are not optimized or qualified for the DSG process. Furthermore, the interaction of a DSG solar field hooked up directly to a steam turbine has to be demonstrated on a realistic pre-commercial scale, e.g., the demonstration plant collector field must have at least four parallel collector loops, each of which has to be the same length as the collector loop in the later commercial collector field. In other words, the demonstration collector field has to be a scalable fraction of the commercial collector field. This is illustrated in Figure 5.3. Consequently the test set-up where the components will be tested during development has to be a scalable fraction of the latter complete system too. Accordingly the medium to long term activities of the project consortium are subdivided into three phases:

1. Phase I: Detailed design, erection and operation of a test set-up
2. Phase II: Detailed design, erection and operation of a demonstration plant
3. Phase III: Detailed design, erection and operation of a commercial plant

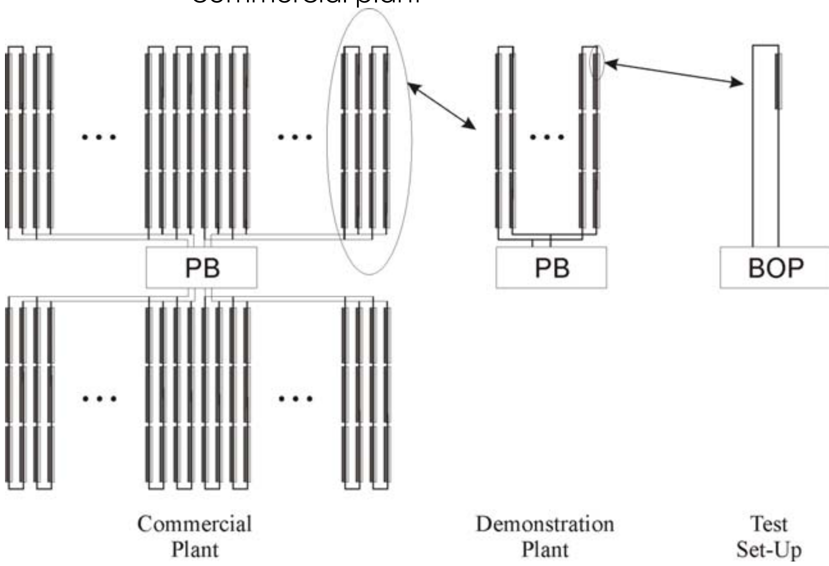

Figure 5.3 Illustration of the 'down-scaling' of a commercial DSG collector field during project evolution (PB = power block, BOP = balance of plant).

DIVA, TEWA

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Participants: SCHOTT (D), DLR (D), FLAGSOL GmbH (D), Fraunhofer ISE (D)

Funding: Co-funded by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).

Within the last year several detailed improvements of Schott's PTR 70 parabolic-trough receiver have been developed, e.g., a new, significantly improved absorber coating system was developed in the DIVA Project. Measurements taken were studied in an attempt to solve the "hot receiver problem" (diffusion of hydrogen into the evacuated annulus) in the TEWA project. The resulting heat losses were quantified. At the present

Figure 5.4 Production of SCHOTT PTR 70® receivers

time, the effect and capacity of different getters are being measured.

In addition, the development of direct steam generation receivers has begun. Tubes were dimensioned to comply with the EN 13480-3, AD2000 and ASME B31-3 (pressurized vessels and piping) standards. The first prototypes will be manufactured the next year.

In 2007, our factory in Mitterteich was awarded by a consortium of WHU, INSEAD and the German journal "Wirtschaftswoche" second best production plant in Germany and one of the best in Europe.

DIVA

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

The goal of the German DIVA R&D project is to determine the economic potential of direct steam generation (DSG) in parabolic troughs, especially at live-steam temperatures of up to 500°C and the development of an absorber tube suitable for this higher operating temperature.

To do this, the levelized electricity costs (LEC) for sixty different DSG systems (five live-steam temperatures, three live-steam pressures, four capacities) are calculated and compared. In addition, the LEC for these systems is calculated for three different sites in Spain, Morocco and the USA. An appropriate absorber coating was developed by SCHOTT for this increased operation temperature.

The LEC of a solar thermal power plant is mainly determined by the investment required and the yearly plant electricity production at a specific site. To determine the investment, the collector field conceptual design and power block of each system must be known. The yearly electricity production is found by means of yearly performance calculations using the IPSEpro© commercial heat balance calculation program.

For small capacities of 5 MW as well as for a commercial 50-MW size, live-steam parameters of 100 bar/500°C yield the lowest LEC. Depending on the site, there is about a 4% benefit compared to the most attractive 400°C option. In addition to this reduction in LEC the steam-to-steam heat exchanger used for reheating in the lower-temperature power blocks can be omitted, causing a further investment reduction not considered in this study. In a next step, the economic model will be improved and the DSG systems will be compared to reference a SEGS-type solar thermal power plant.

A new selective absorber coating (NAC) was produced in the production line by magnetron sputtering of various metals with and without reactive gas onto a 4-m-long stainless steel tube. The NAC design basically consists of a high-quality reflector coating, a cermet coating to absorb from 0.25 nm to approx. 1.4 µm wavelengths, and finally, an antireflection coating. High solar absorption ($a > 95\,\%$), low thermal emission ($\varepsilon < 12\,\%$), and long stability at high temperature were achieved with the new selective absorber coating. Figure 5.5 shows the

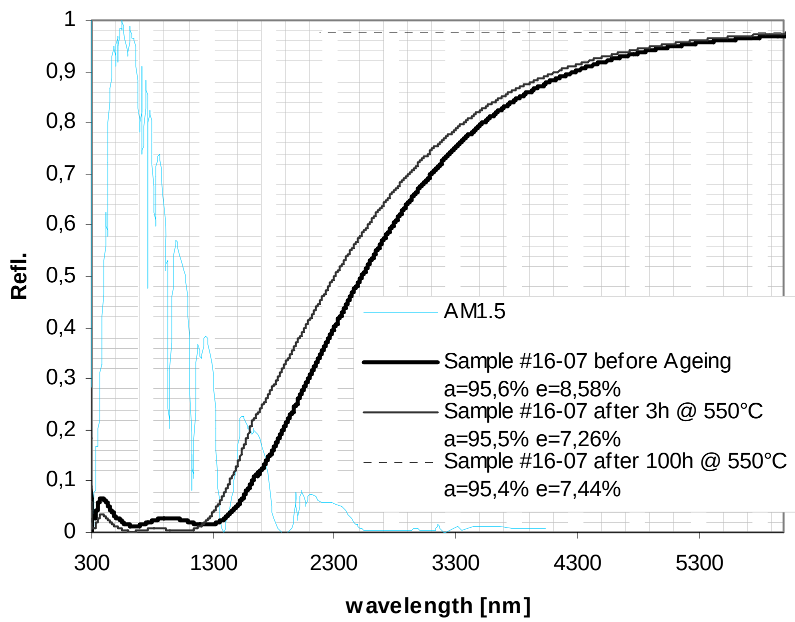

Figure 5.5 Reflection's curve of the new selective absorber coating before and after ageing test.

reflectivity of the new selective absorber coating before and after tempered testing under vacuum at 550°C for 3 and 100 hours. The whole curve shifts slightly toward the lower wavelengths after tempering, inducing an improvement in thermal emission, while solar absorption remains unaffected. Compared to the commercial selective absorber coating, NAC significantly improves thermal emission of approx. 5 %.

DEVELOPMENT OF DREHFLEX SYSTEM CONNECTION TO HCE

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This new connector design can be employed for parabolic-trough collector technology plants. It is a flexible connection for stainless-steel thermal-oil flexible hose assemblies used as inlet and outlet manifolds on the rotating rows of parabolic reflectors. The connection to the absorber tube is by the rotating, self-adjusting reflectors. The design has the following advantages:

- Compensates for expansion of the rotating HCE during daily warm-up and cooling down
- Force transmission into the trough structure is significantly reduced and now insignificant
- Uniform installation and movement of the flexible system between HCE and piping
- Break-away forces are negligible due to assisted rotation.
- Only one sealing point
- Uniform position of a single rotation joint – a big advantage for maintenance
- The same rotary bearing design serves as the connection on the end of the row and in between.

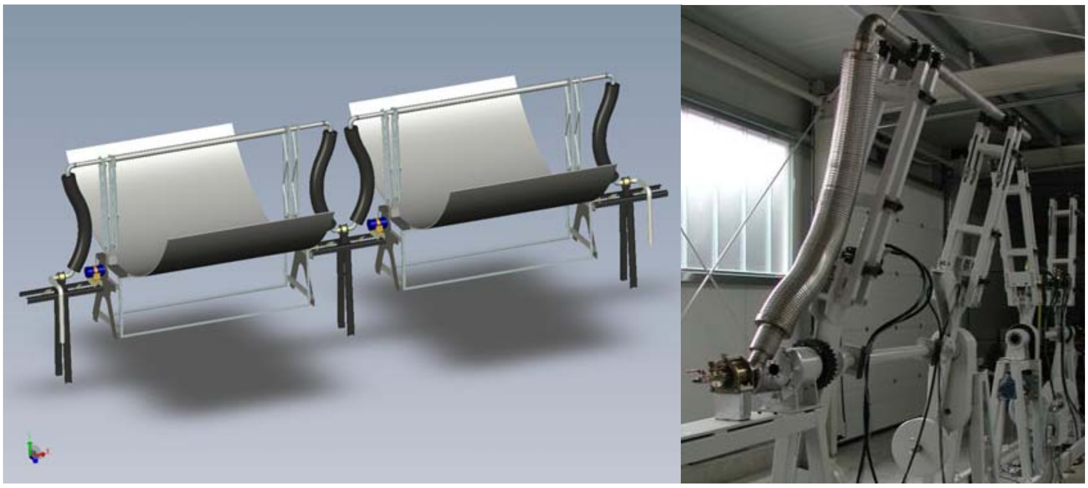

Figure 5.6 left: Model of DREHFLEX; Right: Test rig

FRESNEL SYSTEMS

FRESDEMO

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

The FRESDEMO Fresnel demonstration plant was planned and built by the MAN Ferrostaal Power Industry, in collaboration with its technology partner Solar Power Group GmbH, and with scientific assistance from the German Aerospace Center (DLR), the Fraunhofer Institute of Solar Energy Systems (ISE) and PSE GmbH.

MAN Ferrostaal is responsible for FRESDEMO project co-ordination, optimization of the collector structure, operation and control of the test collector and system economic analysis. The Solar Power Group (SPG) designed and engineered the collector, supported the construction and developed O&M procedures. Fraunhofer ISE was responsible for system technical and economic optimization of the conceptual design, absorber tube coating and front-surface-reflecting secondary mirrors, as well as optical measurement of the collector components during manufacturing. DLR performed on-site component optical characterization, assisted construction in Spain, developed start-up and shutdown procedures and analyzed collector performance in cooperation with ISE and PSE. PSE developed the tracking and control concept for the primary mirrors and is the supplier of the antireflective glass plate.

The pilot plant (Figure 5.7) is intended to demonstrate the technological maturity and commercial potential of the tech-

Figure 5.7 Photo of the MAN linear Fresnel demo collector erected on the Plataforma Solar de Almería (PSA).

nology. The test period will run until the end of 2008. During this time all essential tests will be carried out as well as improvements to the plant. It may be extended, however, for another two years to use the installation as test bed for trial of various emerging/new components under different operating conditions.

The collector with a total length of 100 m and width of 21 m is equipped with Primary Mirrors with a total surface area of 1.433 m^2. The total number of 1200 mirrors is installed in 25 rows over the whole length of the module. The collector is designed for operation with direct steam generation at a maximum pressure of 100 bar and a steam temperature of 450°C.

Land was provided by CIEMAT at the Plataforma Solar de Almería (PSA), where the demonstration collector is connected to the existing DISS test facility [5.02] with water and steam supply, allowing testing in three different operating modes, preheating, evaporation and superheating.

Literature: [5.02].

Development of an Advanced, High-Temperature Linear Power Tower System

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Participants: SkyFuel, Inc.

Funding: U.S. Dept. of Energy funding of $435,000, plus $154,000 funding by SkyFuel

SkyFuel is developing an advanced CSP system, using linear Fresnel reflective technology, to achieve significantly lower delivered electricity costs from utility-scale solar thermal power plants. The advanced CSP system is expressly designed to use molten salt heat transfer fluids (HTF) to enable higher operating temperatures and direct thermal storage (i.e. the HTF in the solar field is also the thermal storage medium). This eliminates the need for expensive and performance-reducing heat exchang-

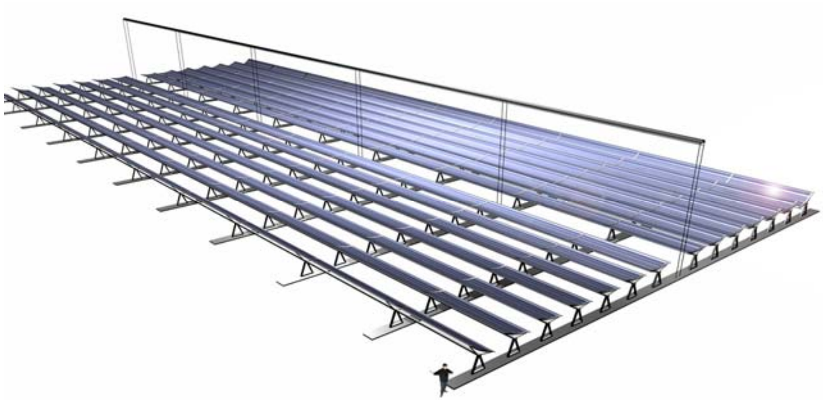

Figure 5.8 Linear Power Tower™, Single Segment
NOTE: Notice the human figure for size comparison.

ers between the solar field subsystem and the thermal storage subsystem. Lowering the costs and improving the performance of thermal storage in this way, while simultaneously simplifying the overall system configuration, will reduce the cost of energy delivered from CSP plants, increase overall plant capacity factors, add dispatchability to plant output, and enhance the value of the delivered energy. SkyFuel refers to its own unique linear Fresnel design as *Linear Power Tower™ (LPT™)*.

FRESQUALI - Qualification of Linear Fresnel Collectors - Adaptation and Development of Optical and Thermal Testing Techniques

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Participants: Fraunhofer ISE

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

Optical and thermal qualification assists manufacturers and construction companies in controlling the optical and thermal performance of concentrating collectors. In the national FRESQUALI project, Fraunhofer ISE develops measurement techniques for key thermal receiver components, and secondary and primary mirrors.

Optical quality of the primary mirror field is a main factor for good performance of the Linear Fresnel Collector. Field optical efficiency is influenced by material properties, tracking errors, frame torsion and contour accuracy.

The active Fringe Reflection Technique (FRT) makes it possible to build a very precise, robust, flexible measurement setup on the basis of just a monitor or a beamer with a projection surface and a camera for intensity images of distorted regular fringe reflections. An analysis of the reflected pattern yields a mirror surface gradient as a first result. By numerical integration or differentiation, height profiles or curvature may be calculated. Dynamic or active techniques are used with sinusoidal gray value patterns generated by the computer. The patterns can be adapted to the required spatial resolution. During the examination of primary mirrors, many details seen may be irrele-

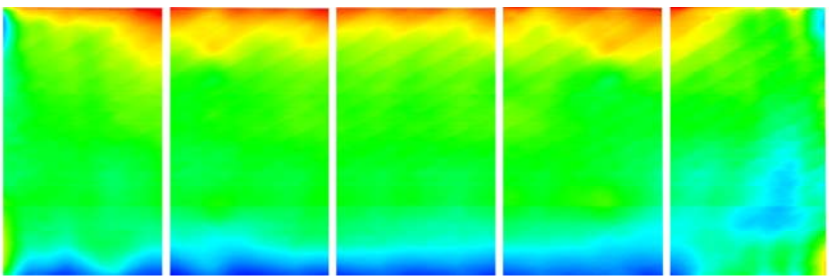

Figure 5.9 Map of transversal slope deviations of a primary mirror in mrad. (green: +- 1mrad); at the edges the mirror is more flat (red/blue).

vant for production-line quality control, but are useful for component optimization, for which specifically adapted passive printed patterns might be a reasonable solution.

The FRT has now been used in the laboratory, during on-site production and in the field. Primary mirrors with long focus lengths as well as mirrors with short focus lengths have been tested.

Literature: [5.03] and [5.04]

STORAGE SYSTEMS

ITES

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

Cost-effective storage systems demand adaptation of the storage technology to the heat source and the consumer. For direct steam generation, there is a significant advantage, when specially adapted storage modules for preheating, evaporation and superheating are employed. For the preheating and superheating range of the heat transfer fluid water/steam, sensible heat storage is beneficial, while for the two-phase flow during evaporation and condensation of the heat transfer fluid, phase change material (PCM) technology is most efficient as thermal storage.

The aims of the ITES project are the development of a complete storage system for solar direct steam generation with specially adapted storage modules for preheating, evaporation and superheating and the adaptation of the process control system to the specific requirements of solar thermal power plants.

For preheating and superheating, the concrete storage technology developed by Ed. Züblin AG and DLR for trough power plants with thermal oil as heat transfer fluid, will be adapted to the requirements of the water/steam heat transfer fluid and to a storage temperature of 500°C in the project ITES.

PCM-storage is being developed by DLR. Sodium-nitrate, with a melting temperature of 306°C, has been selected as the phase change material. For efficient storage design, a heat transfer structure is applied to overcome the very low thermal conductivity of the salt.

Demonstration of two storage modules, a PCM module for the evaporation/condensation range and a concrete module for the superheating range, will start in 2008 in the test loop to be constructed under the REAL-DISS project at the ENDESA Litoral Power Plant in Carboneras, Spain. The demo storage system is designed for a total power of about 1 MW and 1 MWh capacity.

Thermal storage system integration in a commercial-scale solar power plant is analyzed for 50 MW_e plants by DLR and Siemens. Compared to oil-based parabolic-trough systems, the specific requirements for integration of steam from the two sources, solar field and storage system, are identified as a basis for development of appropriate technical solutions. Simulation capabilities especially for the dynamic behavior of the whole system are extended. Dynamic simulation of the system and the components is used to study subsystem interaction in order to define key component technical requirements and design the process control system structure. Online methods for optimized plant operation are also developed in this task.

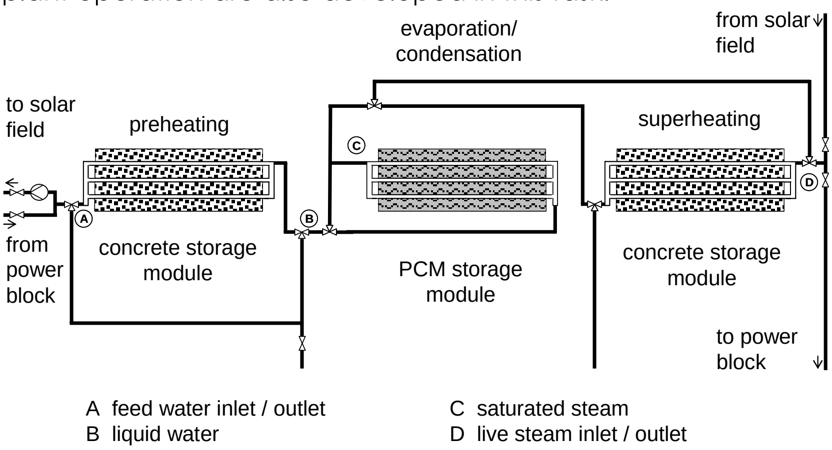

Figure 5.10 Main storage configuration for two-phase heat transfer fluids.

DISH CONCENTRATOR SYSTEMS/ADVANCED APPLICATIONS

Parabolic Dish Development in Mexico

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Funding: IIE-Fideicommissum (FICYDET)

The Instituto de Investigaciones Eléctricas (IIE) has already been working on the development of Solar Concentrating Technologies for several years. At the present time, part of the effort is devoted to this line of research and technology development focuses on the design and construction of a parabolic dish for electricity generation. The project began in the year 2000 with the primary objective of procuring a small unit 5-to-

7.5-kW$_e$ parabolic dish/Stirling system from international industry or government agency in order to acquire practical experience. At the beginning of 2001 the project was reoriented toward the design, local manufacture and construction of a parabolic dish prototype, with the 10-kW$_e$ nominal power of the Stirling engine provided the IIE by CIEMAT (Spain) by cooperation agreement. Unfortunately, toward the end of 2002, the project was canceled and the system remains unfinished. At this stage of the project, besides the conceptual and detailed engineering, it was also possible to construct some elements of the parabolic dish, such as the dish frame and the twelve facets that compose it and some smaller elements. After many efforts to reactivate the project it was finally restarted at the end of 2006 in order to conclude the general project plan of work. The Mexican parabolic dish is now in the last stage of construction and all its components are expected be integrated in the next several months, when the first operating tests will begin [1]. The solar concentrator, which is one of the elements that were manufactured at the end of 2002, has a 7.5-m diameter parabola divided into twelve facets. The facets were made of a fiberglass substrate and anodized aluminum sheet reflective surface. Each facet is 3.5-m long, with an arc length of 1.95-m at the outer diameter and 0.15-m at the inner one. One facet was left exposed to ambient conditions to test the bonding technique. When the project was stopped, the facet was left unattended. At the end of 2006, when the facet was inspected, it was found that the epoxy resin had failed and aluminum surface aging was evident. It was therefore decided to replace the aluminum with a silvered thin-glass (1.0 mm) mirror and the epoxy resin with adhesive transfer tape. Other activities during 2007 were manufacture of the metal machine support structure, elevation ring, base and horizontal orientation ring [2]. All of these elements are being assembled as is shown in Figure 5.11. The Stirling engine available at the time was from one of the Schlaich Bergermann und Partner (SBP) 7.5-meter dish sys-

Figure 5.11 Metal structure assembly

tems, in the DISTAL I project at the Plataforma Solar in Almería, Spain. When the DISTAL project ended 2002, the IIE received two engines through a cooperation agreement with the CIEMAT (Spain). At that time, the engines had been recently been removed from the dishes and were still in operating condition.
After the interlude (2002-2006), the engines were recently inspected, and no longer seem to be in good condition. The IIE is currently looking into the possibility of making an arrangement with the owner of the engine's proprietary license in Germany, SBP.

Literature:
[5.05]-[5.06]

Hybrid Solar Dish/Stirling Power System

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Sacramento Municipal Utility District
California Energy Commission

Funding: $951,000

This project, managed by the Sacramento Municipal Utility District and funded by the California Energy Commission through their Public Interest Energy Research (PIER) program, resulted in the integration and demonstration of a 22-kW solar dish/Stirling electric power system hybridized with natural gas. The system was operated as a true hybrid system, with natural gas augmenting the available solar energy so the Stirling engine operated at a constant, full-power output under all conditions of sunlight, day or night. The power from the system was deli-

Figure 5.12 SAIC Solar Dish/Stirling Hybrid System in Operation

vered directly to the utility grid at 480 VAC.

For this project Science Applications International Corporation (SAIC) upgraded an existing solar dish concentrator system with advanced fixed focal length mirror facets, variable-speed DC drive motors, and an STM Power Beta Stirling engine (a precursor to commercial production units) to produce the 22-kW hybrid solar dish/Stirling power system. The system was operated for ten months between September 2003 and December 2004 in order to characterize its performance and measure and demonstrate its reliability. During that period, the system operated over 780 hours in solar hybrid mode and delivered 14.3 MWh of energy. It also operated 315 hours in gas-only mode, delivering 5.5 MWh of energy. In the course of operation, the system exhibited an increasing efficiency and a Mean Time Between Failures (MTBF) that was three times longer than existing SAIC dish/Stirling systems.

The demonstration of a hybrid solar dish/Stirling system provides a dispatchable, efficient system that can be employed in various markets as a viable alternative for solar electric power production.

Literature: [5.07][5.08]

Solar Dish/Photovoltaic Power System

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Participants: Science Applications International Corp.
University of Nevada, Las Vegas
National Renewable Energy Laboratory

Funding: $1,200,000

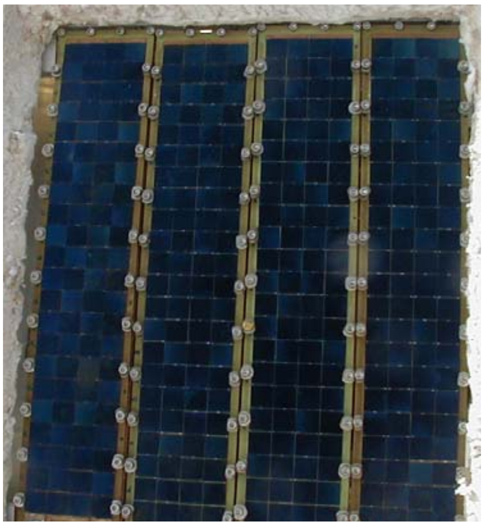

Figure 5.13 SAIC Solar Dish/PV System in Operation (left); AMONIX Close-Packed Concentrating PV Receiver Modules (right)

This project had as its goal to develop and demonstrate a concentrating dish/PV system for utility-scale application, based on the SAIC faceted dish concentrator and a monolithic PV receiver. For this project Science Applications International Corporation (SAIC) upgraded an existing solar dish concentrator system with specialized fixed focal length mirror facets, variable-speed DC drive motors, and a crystalline silicon PV receiver provided by Amonix Corp. to produce a solar dish/PV power system. The project successfully demonstrated operation of the dish system, receiver cooling and heat rejection systems, inverters, and PV receiver modules. The system was operated on-sun for over 100 hours with a partial receiver. This represented the first-ever operation of a large concentrating dish/PV system in the United States.

Literature: [5.09]

Big Dish Solar Thermal Concentrators for Integrated Energy Solutions

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Participants: Wizard Power Pty Ltd, Australian National University

Funding: AUD7m, part funding from Australian Government Renewable Energy Development Initiative (REDI)

The core activity of this project is the re-engineering of the ANU Big Dish concentrator technology for cost effective mass production. A new design has been developed that incorporates innovative features for which IP protection is currently being arranged. Key features include the use of square mirror panels with a 1.2-m side dimension. Identical mirror panels are used throughout and Glass on metal laminated mirror is used. The frame work system has also been varied from the approach used in the original ANU prototype. Size has increased to an aperture area of 500 m^2. Construction has commenced on a first prototype on the ANU campus, immediately adjacent to the existing 400 m^2 unit.

The project also incorporates associated research on a range of possible energy conversion systems plus planning and the first stages of implementation of a multi-dish power system.

Ammonia Dissociation Based Solar Energy Storage for Multi-Megawatt Baseload and on-Demand Power

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Participants: Wizard Power Pty Ltd, Australian National University

Funding: AUD14.8m, part funding from Australian Government Advanced Energy Storage Technology (AEST) Program

This project is just commencing and will involve the construction of a first multi-dish demonstration power system. Final configuration is yet to be finalized, however a minimum of 4 of the

Generation II Big Dish concentrator units will be used and ammonia based thermochemical energy storage will be incorporated. The site identified is in Whyalla South Australia as illustrated in Figure 5.14.

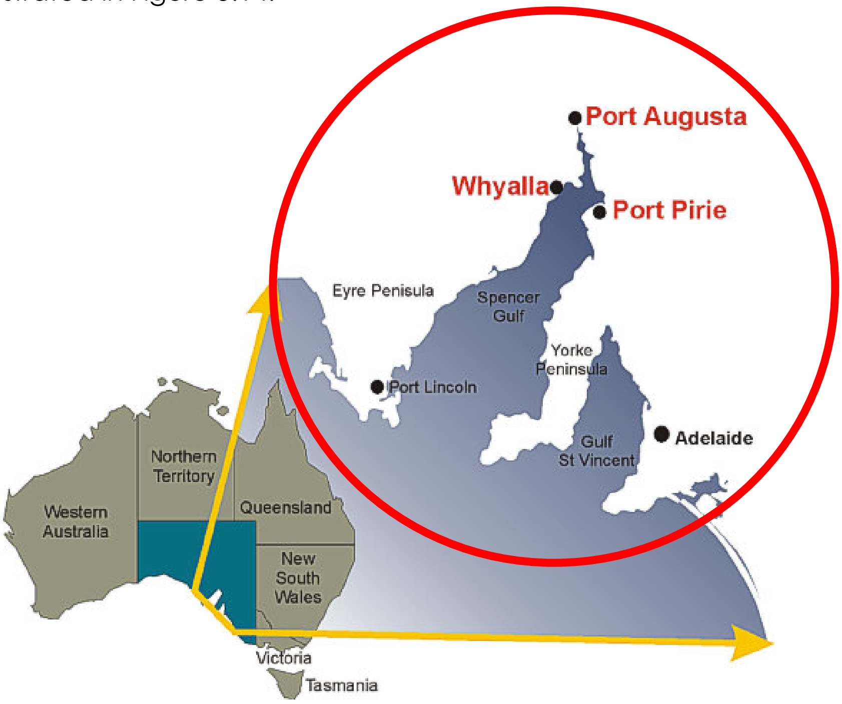

Figure 5.14 1st Big Dish demonstration power system planned for Whyalla, South Australia

5.3.2 Sector III.2: Supporting Tools and Test Facilities

This sector covers the following activities:

- Simulation and Software Activities
- Networking / Standardization
- Measurement Systems
- Test facilities

Water-efficient cooling of solar thermal power plants

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Participants: DLR German Aerospace Center; National Renewable Energy Laboratory

Funding: BMU German Federal Ministry for the Environment (Efcool-Project), DLR and NREL

The purpose of this activity is to identify and optimize cooling concepts for solar thermal power plants at sites with limited water availability, and evaluate the impact of the different cooling options on the LEC. This includes an overview of existing cooling technologies, including different combinations of dry and wet cooling (hybrid systems) and analysis of options to shift the cooling load to evening and night hours through storage, which

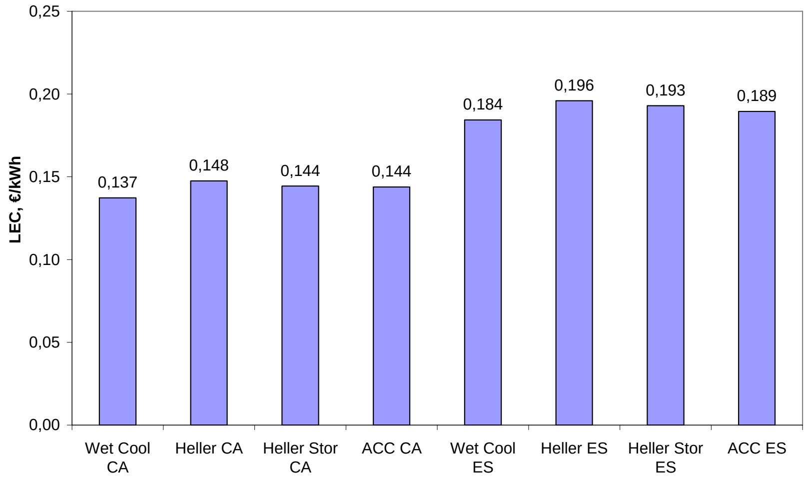

Figure 5.15 Simulated LEC cost for different cooling operations at sites in California (CA) and Spain (E)

could reduce the investment and operating cost of the cooling system by taking advantage of the extended operating time and lower ambient temperature. To evaluate these different options, a simulation tool had been developed for analyzing the LEC based on relevant weather conditions at different project sites. Recommendations for the design of suitable cooling systems are derived from the analysis of different case studies, especially for parabolic trough plants operating with thermal oil as heat transfer fluid.

For a reference case 50-MW parabolic-trough power plant wet cooling, air-cooled condensers (ACC), and a Heller System with or without storage via water tanks were simulated for different sites. LEC results for ACC and Heller System with storage are close and do not allow for general conclusions, requiring specific studies for a given project site and configuration.

Literature: [5.10] and [5.11]

SAPHIR

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Participants: DLR

Funding: BMU German Federal Ministry for the Environment, and DLR

Within this project, DLR is developing a new optical measurement method that simplifies and optimizes the mounting and canting of heliostats and assures their optical quality before commissioning the solar field. This method is based on the reflection of regular patterns in the mirror surface and their distortions due to mirror surface errors. Present measurement resolution is one million points per heliostat with a measurement uncertainty of less than 0.1 mrad and a measurement time of less than 5 minutes per heliostat. Current work is the automization of the system so measurement of an entire heliostat field can be done automatically during one night. Figure 5.16 shows an example of a reflected stripe pattern and slope errors of a heliostat measured at the PSA.

Additional optical measurement methods based on edge detection are developed to automatically check the tracking accuracy of the heliostat field during operation using the same hardware. Existing optical measurement systems for temperature and flux density distribution of small-scale prototype receivers are extended to allow measurement of these parameters directly on the surface of large-scale receivers during operation of commercial power plants.

Based on the knowledge acquired in this project, relevant parameters for the assessment of heliostat fields during design, manufacturing and operation are defined and appropriate methods for their measurement are proposed.

Literature: [5.12] and [5.13]

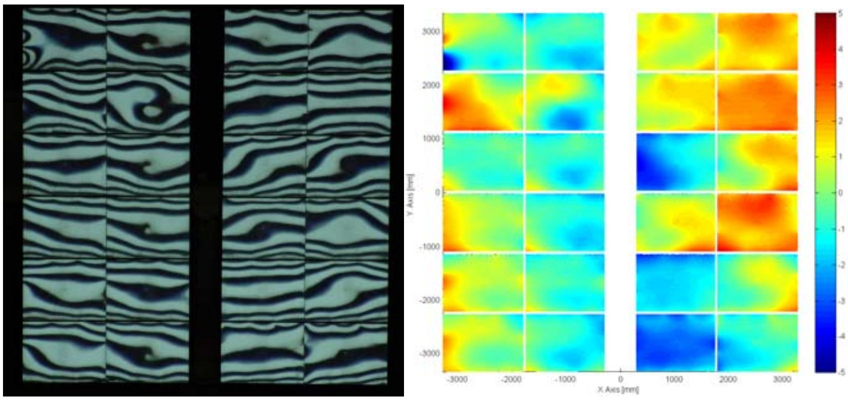

Figure 5.16 Reflected horizontal stripe pattern (left) and measured slope errors in vertical direction (right) of a heliostat at PSA measured with the reflection method

5.3.3 Sector III.3: Advanced Technologies and Applications

SolarPRO II:

Development of preindustrial prototype to generate high-temperature SOLAR PROcess heat: testing and characterization of its application to several high-temperature industrial and waste removal processes.

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Participants: Plataforma Solar de Almeria-CIEMAT (E).
Univ. Seville Mechanical and Materials Engineering Dept. (E), Co-ordinator
Institute of Ceramics Technologies. Castellón (E).
Fluid Mechanics Dept.
Polytechnic Catalonian University (E).

Funding: Spanish Ministry of Science and Technology. National Program of Scientific Research, Develop-

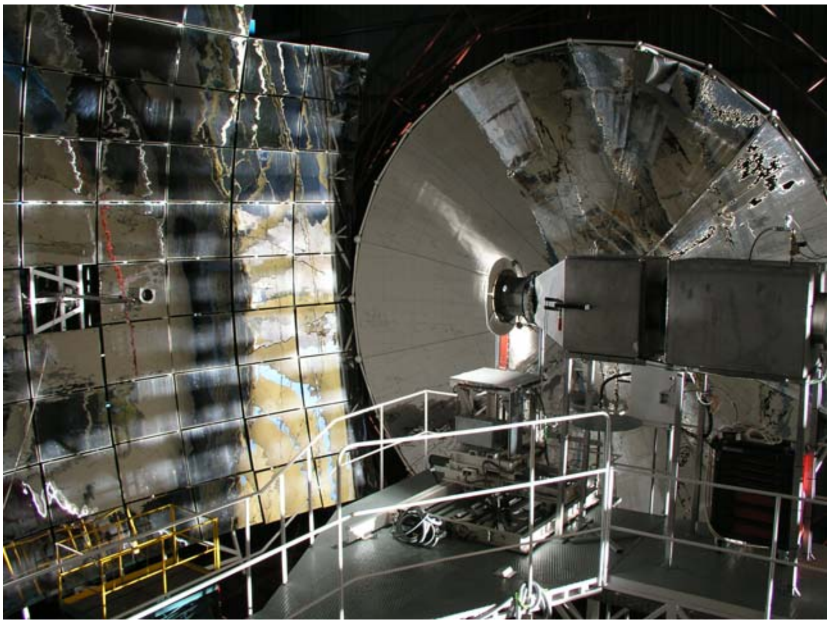

Figure 5.17 Processing plant with volumetric receiver at the PSA Solar Furnace

ment and Technology Innovation 2004-2007 (ENE2006-13267-C05-01/ALT)

SolarPRO II develops pilot-plant-scale prototypes for the study and characterization of various industrial and waste treatment processes with solar process heat, which were already shown to be technologically feasible in SolarPRO I. These processes, of great scientific and technological interest, need to be studied, developed, scaled up and characterized to demonstrate and strengthen the pre-industrial development of the technology. Furthermore, for certain processes, such as waste treatment, it is planned to study the design and development of prototypes to be hooked up to parabolic dishes that can work as small modular production units for the on-site treatment of raw materials or waste in small industries, research centers or remote areas.

Processes to be studied are basically classified in three groups:

- Industrial manufacturing processes.
- Materials treatment processes
- Solid waste treatment processes.

CIEMAT- CENIM Agreement:

Thermal treatment of metals with concentrated solar energy and characterization of solar concentrators.

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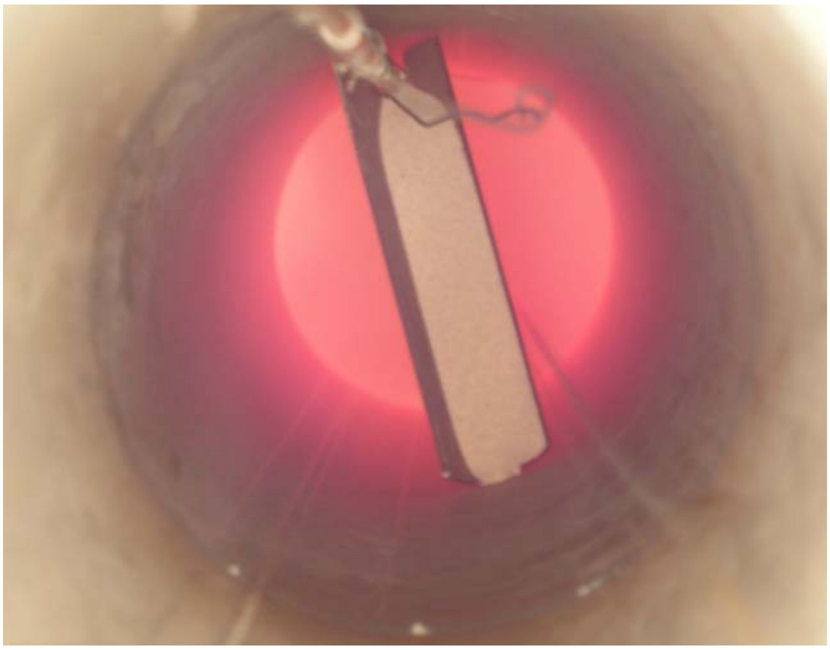

Figure 5.18 Internal view of indirectly heated solar fluidized bed

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Participants: Plataforma Solar de Almeria, CIEMAT (Spain), CENIM - National Center for Metallurgical Research, CSIC (Spain)

Funding: Agreement CENIM-CSIC, PSA-CIEMAT (2006-2008)

A new fluidized bed reactor with indirect solar heating and open volumetric receiver has been developed by CENIM and CIEMAT for installation in the PSA Solar Furnace. This reactor has an innovative design that allows a gas flow to be uniformly heated up to 1150 K and applied to different industrial processes and materials treatments. The main characteristics of this reactor are its good thermal transference, uniform heating of the gas flow, the possibility of using different gases, and its ability to maintain the temperature constant as opposed to transitional weather changes.

During 2006 and 2007, several tests softening aluminum alloys and hardening steel by heating in the bed and quenching it in water or oil were performed. These tests demonstrated the feasibility of a solar-heated fluidized bed as a thermal reactor for medium and high temperature metallurgical applications.

Future applications during 2008 will be other thermal treatments, coating of metals in reactive atmospheres, by nitriding, carburizing, etc.

5.4 Outlook

Public and political awareness of CSP technology has experienced strong growth in several countries, especially Spain, during the last few years, creating an attractive market. Accordingly, many projects are now underway or in an advanced stage of planning. This creates a stimulating environment for

R&D work to further improve components, develop standardized testing methods and investigate advanced concepts for power plant design and operation. Therefore, in the near future, a significant effort will be devoted to further improve tools for quality and performance assurance, especially in CSP plant concentrator and receiver elements, and demonstrate new storage concepts to drive down cost and assist in power plant operation. A new activity regarding efficient water cooling of CSP plants is being initiated to address this important issue.

5.5 Meetings, Reports Publications

5.5.1 Meetings

A Task Meeting was held during the ISES International Solar Energy Conference in Beijing, China on September 19, 2007, in the framework of a CSP Forum organized during the conference.

5.5.2 Literature

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[5.03] Heimsath A., Bothe Th., Li W., Tscheche M., Platzer, W.: *Characterization of Optical Components for Linear Fresnel Collectors by Fringe Reflection Method*, Proceedings of the 14th SolarPACES International Symposium, Las Vegas, USA (2008), to be published

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[5.06] Ramos, C. Ramírez, R. Lagunas, J., Desarrollo de la Tecnología de Plato Parabólico en el IIE. XXXI Semana Nacional de Energía Solar, Zacatecas, Zac., Mexico, Octubre 2007.

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[5.08] Final Report: "Solar Dish Concentrator With Stirling Engine," Contract 500-00-034, California Energy Commission PIER Renewables Program, March 2006.

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[5.12] S. Ulmer, M. Röger: Automatisierte hochaufgelöste Vermessung der Spiegelfehler von Heliostaten. In: 10. Kölner Sonnenkolloquium, DLR, Cologne, 21. June, 2007.

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[5.14] Cañadas, I., Téllez, F., Rodríguez, J., Martínez, D., ''SOLARPRO': A survey of feasible high temperature industrial applications of concentrated solar energy'. *Proceedings of 13th International Symposium on Concentrated Solar Power and Chemical Energy Technologies*. Seville (Spain) 20-23 June 2006. ISBN: 84-7834-519-1

[5.15] Cañadas, I., Martínez, D., Téllez, F., Rodríguez, J., Feasibility Use of Solar Thermal Energy in High Temperature Industrial Processes. *Proceedings of International Conference On Renewable Energies and Water Technologies*. Roquetas de Mar - Almería (Spain). 6-8 October 2006. ISBN 84-933658-3-1

[5.16] Cañadas, I., Téllez, F. Rodríguez, J., Martínez, D., Results of preliminary characterization of a new solar device for high-temperature process heat, accepted for publication at *Journal of Solar Energy Engineering*

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Part 6: Status Report Task IV: Solar Heat for Industrial Processes (SHIP)

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6 Task IV: Solar Heat for Industrial Processes

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Subtask Leaders: Riccardo Battisti, Rome University
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Mathias Rommel, Fhg-ISE, Hans Schnitzer, JOINTS

(Source: PSE, Freiburg)

6.1 *Nature of Work and Objectives*

Around 168 million m² of solar thermal collectors, corresponding to an installed capacity of 118 GW_{th}, had been installed worldwide by 2006. Until now, the widespread use of solar thermal plants has focused almost exclusively on swimming pools, domestic hot water preparation and space heating in the residential sector.

The use of solar energy in commerce and industry is currently insignificant compared to swimming pools and the household sector. Most solar applications for industrial processes have been used on a relatively small scale and are mostly experimental in nature. Only a few large systems are in use worldwide.

However, if one compares the energy consumption of the industry, transportation, household and service sectors in OECD countries, industry has the highest share of energy consumption with approximately 30%, followed closely by the transportation and household sectors.

The major share of the energy, which is needed in commerce and industry for production processes and for heating production halls, is below 250°C. The low temperature level (<80°C) complies with the temperature level that can easily be reached using solar thermal collectors already on the market. The principles of operation of the components and systems apply directly to industrial process heat applications. The unique features of these applications lie on the scale on which they are used, system configurations, controls needed to meet industrial requirements, and the integration of the solar energy supply system with the auxiliary energy source and the industrial process. For applications where temperatures up to 250°C are needed, the experiences are rather limited and suitable components and systems are missing. Therefore, for these applications the development of high performance solar collectors and system components is needed.

To be able to make use of the huge potential for solar heat in industry and to open a new market sector for the solar thermal industry, SHC Task 33/IV carried out potential studies, investigated the most promising applications and industrial sectors for solar heat and optimized, developed and tested solar collectors for medium temperature applications (up to approximately 250ºC). The development of integral solutions for solar thermal energy applications for given industrial processes (based on the "PINCH-concept") was also one of the main topics of this Task. Furthermore, the design and erection of 9 pilot plants was carried out in co-operation with industry.

6.2 *Scope of the Task*

The scope of the Task is solar thermal technologies for converting solar radiation into heat, (i.e., starting with the solar radiation reaching the collector and ending with the hot air, water or steam transferred to the application.) The distribution system, production process and/or optimization of the production process are not the main topics of the Task. However, influences on the production process and the distribution system arising from the solar character of the heat source will be studied within the Task framework.

Applications, systems and technologies, which were included in the scope of this task, are:

- All industrial processes where heat up to a temperature of approx. 250°C is needed.
- Space heating of production or other industry halls is addressed, but not space heating of dwellings.
- Solar thermal systems using air, water, low-pressure steam or oil as a heat carrier, i.e. not limited to a certain heat transfer medium in the solar loop.
- All types of solar thermal collectors for an operating temperature up to 250°C are addressed: uncovered collectors, flat-plate collectors, improved flat-plate collectors - for ex-

ample airtight collectors filled with inert gas, evacuated tube collectors with and without reflectors, CPC collectors, and small parabolic trough collectors.

6.3 *Organization and Structure*

To accomplish the objectives of the Task, the Participants carried out research and development in the framework of the following four Subtasks:

Subtask A: Solar Process Heat Survey and Dissemination of Task Results
(Lead Country: Italy)
Subtask B: Investigation of Industrial Energy Systems
(Lead Country: Austria)
Subtask C: Collectors and Components
(Lead Country: Germany)
Subtask D: System Integration and Demonstration
(Lead Country: Germany)

6.3.1 Collaboration with other IEA Programmes

Due to the complementary background and know-how of the participants of the Solar Heating and Cooling and the SolarPACES Programs, significant synergies were expected from collaboration. Therefore, it was agreed to cooperate with the SolarPACES Program on a “moderate level” according to the SHC “Guidelines for Coordination with other Programs.”

6.4 *Activities during 2007*

6.4.1 Subtask A: Solar Process Heat Survey and Existing Plants and Potential Studies

There are currently about 90 solar thermal plants for process heat worldwide, with a total installed capacity of about 25 8 MW_{th} (35,000 m^2). These plants are located in 21 countries and cover many different industrial sectors, showing that solar thermal energy can be used fruitfully in several industrial applications.

A summary table, reporting information about Solar Heat Plants for Industrial Processes (SHIP) worldwide, was developed and uploaded on the internal SHIP website. This matrix collects technical and economic data about the plants.

An analysis carried out shows that, in spite of the low industrial solar thermal plant operating capacity reported (25 MW_{th} out of 118 GW_{th} of solar thermal installed worldwide), potential for EU SHIP applications is quite high and equals 100÷125 GW_{th} (143÷180 millions of m^2), which is 3.8% of the industrial heat demand in EU 25.

This analysis will be described in a specific booklet on potential studies, which will be published in 2008. The main outcome of the work carried out is the harmonisation of the results of the SHIP potential studies in several EU and non-EU countries and their EU-wide extrapolation.

Case studies and economic analysis

In 2007, 19 case studies on solar thermal plants for industrial applications, covering different industrial sectors and several countries were done: 13 from Austria, 2 from Germany, 2 from Nicaragua and 2 from Spain.

Questionnaires for the economic analysis have been collected from Austria, Germany, Italy, Portugal and Spain, including qualitative and quantitative information about current incentive schemes for SHIP plants and the costs of energy and solar thermal plants.

The results will be uploaded on the Task 33/IV internal website.

DISSEMINATION ACTIVITIES

Industry workshops

In 2007, two industry workshops were held in Cologne and in Graz.

The first, held in Cologne (Germany) on March 30, 2007, funded by the German Federal Ministry of the Environment, Nature and Reactor Safety, was attended by 48 participants, mainly from the industry and research sectors.

The Austrian workshop, attended by 112 participants, was held on September 12, 2007 in Graz, Austria. Besides industry and researchers, the participants also included representatives from the Austrian Federal Ministry for Transport, Innovation and Technology as well as representatives from funding agencies.

Industry Newsletter

The third issue of the industry newsletter was published in January 2007. The topics included are:

- Updated statistics on plant survey
- Monitoring results of CONTANK plant
- Design guidelines for space heating of factory buildings
- Solar heat for breweries

The newsletter is also available on the Task website in the following languages: English, German, Italian, Portuguese and Spanish.

The 4th edition of the Industry Newsletter will be published in February 2008.

6.4.2 SUBTASK B: Investigation of industrial energy systems

Matrix of Indicators

A "matrix of indicators" (MATRIX), which is a comprehensive database, was developed in Subtask B as a decision support tool for solar experts. This matrix will facilitate work with industry and the identification of suitable solar applications. MATRIX should make it possible to investigate and calculate the installation of solar heat in production processes without detailed knowledge of the relevant unit operations.

Some industries such as food, chemistry, plastic processing, textile industry and surface treatment can be identified as very promising sectors for solar thermal applications. For these industries, detailed information like general benchmark data, process temperatures, production line flow sheets and generic hydraulic schemes for solar integration can be found in specific Sub-MATRICES.

Investigation of these relevant industries should focus on an integrated analysis of cooling and heating demands, taking into account competitive technologies, when assessing the economic feasibility of solar thermal energy. Among those competing technologies are heat integration, co-generation, new technologies and heat pumps, which are also described in the relevant parts of the MATRIX.

Expansion of the Existing Heat Integration Models

Most industries have demand heat for production and at the same time, produce a good deal of waste heat. Use of this waste heat has the advantage of competing with the heat demand of other processes. Reuse must be done at as high a temperature as possible. The most promising methodology for identifying the maximum heat recovery in a defined system is the pinch analysis. With this tool the minimum heating demand and the minimum cooling demand can also be identified. Within the work of Subtask B a computer program (Pinch Energy Efficiency – PE²), which calculates the recovery potential and designs the technically and economically feasible heat exchanger network for given processes has been developed. The new software PE² fulfills the needs of heat integration calculations in the promising industries.

Within the work of Subtask B a computer program (Pinch Energy Efficiency – PE²), which calculates the heat recovery potential and designs a technically and economically feasible

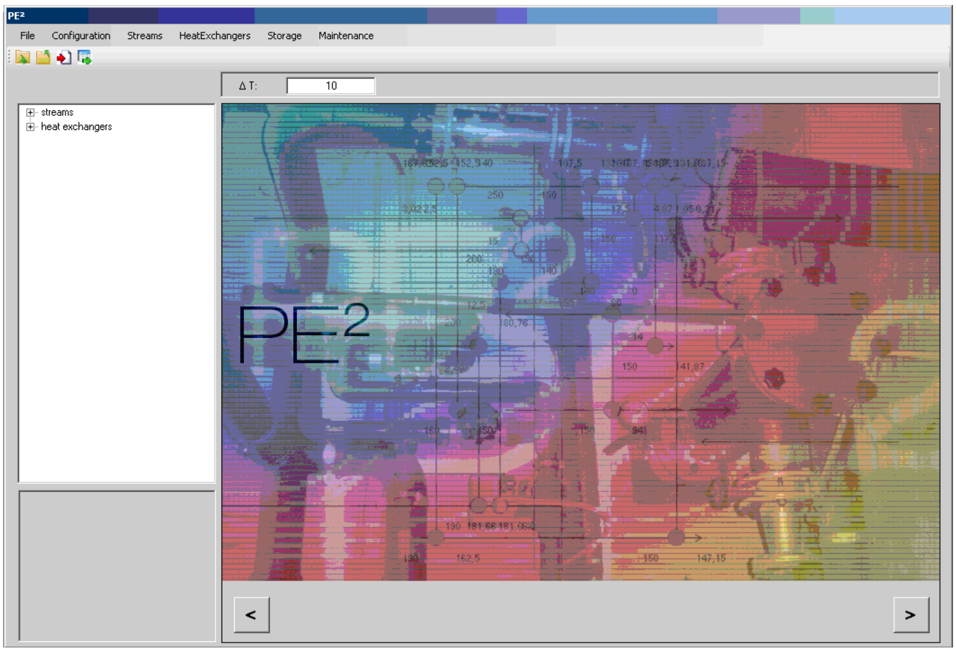


Figure 6.1. Front page of the PE² software, which was developed within Task 33/IV by JOINTS, Austria

heat exchanger network for given processes, has been developed. The new software PE² fulfils the needs of heat integration calculation in promising industries. Automatic calculation of an ideal heat exchanger network (based on mathematical criteria and aiming at maximum energy savings in kWh per year) is one of the main advantages of this developed tool. Furthermore, heat exchanger surfaces may be calculated, as well as a dynamic cost resulting in the payback period of a given heat exchanger network based on user defined economic data, and the visualization of energy savings with the Sankey Editor afford fast energy optimization of a whole company.

Analysis with this tool shows the energy demand remaining at the corresponding temperature after optimization of the processes with heat recovery. It gives the temperature demand for external heat/cold is necessary, which is important information for a possible solar process heat plant.

6.4.3 Subtask C: Collectors and Components

Medium Temperature Collector Developments

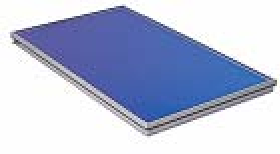
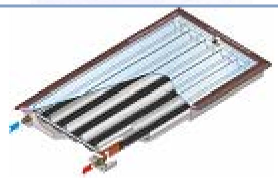
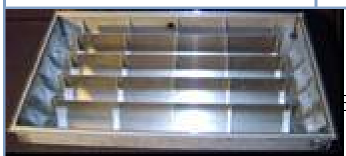
The two final Task experts meetings in Köln, Germany, and Graz, Austria, in 2007, showed that development of Medium-Temperature Collectors continues. Even after the end of the Task, in the next years new developments can be expected to come up.

For example, there is a new, improved CPC collector with evacuated casing under development at ZAE Bayern, Germany. Almost all the prototype components are ready, and the first collector will soon be assembled. Then experimental investigation will be carried out on the collector. First test results are expected to be available in 2008.

The redesign of the Universitat de les Illes Balears CCSTAR collector is now almost finished. The collector is based on the principle of a fixed reflector and tracking receiver. A 25-m² prototype reflector was built. The idea of stepped reflector geometry has been discarded. Investigation carried out so far showed that a reflector with a parabolic shape is accurate enough, as long as the concentration factor is not too high. A continuous surface reflector is easier to manufacture than a reflector with a stepped geometry, and therefore, more cost-effective. First optical studies of the new reflector construction showed quite good results. The geometric concentration factor will be in the range of 11. The prototype reflector was built using reflector material from two different manufacturers. The prototype is due to be available in spring of 2008.

Interesting results with the PSE-Fresnel collector for medium temperature applications were also achieved. Measurements were presented which were taken from the first prototype collector set up in Freiburg, as well as on the second prototype which is set up in Bergamo, Italy. The third prototype using this collector technology was installed in Seville, Spain, in the summer of 2007.

Table 6.1. Collectors developed and investigated in Task 33/IV

	Collector type	Working temperature [ºC]	Heat transfer media	Contact Task 33/IV
Optimised flat plate collectors				
	**2AR flat-plate collector** Double Glazed Flat-Plate Collector with Anti-Reflective Glasses	80 – 150	Water-Glycol	Fraunhofer Institut für Solare Energiesysteme Heidenhofstrasse 2 79110 Freiburg Germany
	**SCHÜCO** Double-Glazed Flat-Plate Collector	80 - 150	Water-Glycol	Schüco International KG Karolinenestr. 1-15 33615 Bielefeld Germany
CPC-collectors				
	**AoSol** Stationary CPC Collector	80 - 110	Water-Glycol	DER/INETI, Edificio H, Estrada do Paço do Lumiar, 22, 1649-038 Lisboa Portugal
	**Solarfocus** Stationary CPC Collector	80 - 120	Water-Glycol	SOLARFOCUS GmbH 4451 St.Ulrich / Steyr Austria
	**ZEA** Evacuated stationary CPC collector	120 - 180	Water-Glycol	ZAE Bayern Walther-Meißner-Str. 6, 85748 Garching Germany
Small parabolic trough collectors				
	**PARASOL** Parabolic Trough Collector	100 – 200	Water or steam	AEE INTEC Feldgasse 19 8200 Gleisdorf Austria

	**SOLITEM PTC 1800** Parabolic Trough Collector	100 – 200	Water	DLR Institut für Technische Thermodynamik 51170 Köln Germany
	**NEP SOLAR** Polymer Carrier PTC	150 – 250	Water	New Energy Partners Pty Ltd Level 2 Suite 1a 802 Pacific Highway Gordon NSW 2072 Australia
	**PTC 1000** Modular parabolic trough collector	80 – 300	Water	Solar-Institut Jülich Heinrich-Mußmann-Str. 5 52428 Jülich Germany
	**CHAPS** Combined Heat and Power Solar collector	80 - 150	Water	Australian National University Centre for Sustainable Energy Systems Department of Engineering, Canberra ACT 0200 Australia
Fresnel collector				
	**PSE** linear Fresnel collector	100 – 400	Water, steam or Thermo oil	PSE Solar Info Center 79072 Freiburg Germany
CCStaR – Concentrating collector with stationary reflector				
	**CCStaR** Concentrating Collector with Stationary Reflector	80 - 140	Water	Universitat de les Illes Balears Palma de Mallorca Spain

These examples and other presentations in the meetings of the Task's last year of operation demonstrated that there is continuing interest in new developments, and that new technical possibilities for different lines of process heat collector development are still coming up.

Process Heat Collector Testing

The work on collector testing and recommendations for testing procedures was continued and finalized. The work on the Round Robin test (which was rather an inter-comparison test) was continued and finalized. Three institutions were involved in this Task 33/IV activity: ITW, Germany, INETI, Portugal and Fraunhofer ISE. An evacuated tube collector with CPC reflector was tested. Three collectors of the same type were first tested at ISE. These measurements demonstrated that the efficiency curves of the three different collectors did not differ by more than 1%.

Results show that there is a certain agreement of the measured efficiency curves within the temperature range in which the efficiency point measurements were actually carried out by all three testing institutions, however, not all tests were really in the temperature range up to 200°C. In fact, the highest collector temperatures during the tests were only about 98°C (ITW) and 114°C (INETI). ISE tested up to 183°C. The differences in the measured efficiency increase very far outside the measurement range. This again shows the unconditional necessity of measuring efficiency and performance of medium-temperature collectors at real temperatures up to 200°C. Figure 6.2 shows the indoor simulator testing facility of Fraunhofer ISE with the new medium-temperature testing device. The diagram shows three efficiency curves which were all measured up to collector inlet-temperatures near to 200°C during the tests. The results of the Task also show that more experiments are needed to determine 2D-Incidence Angle Modifiers for better, more reliable characterisation of medium-temperature collectors.

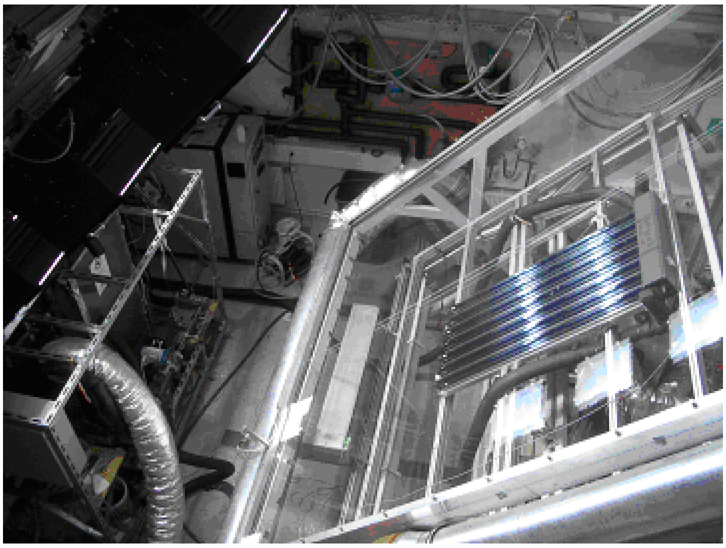


Figure 6.2. Evacuated tube collector with CPC reflector at Fraunhofer ISE in inter-comparison of efficiency curve measurement. The medium-temperature test unit provides accurate measurement up to 200 °C (bottom left in the picture).

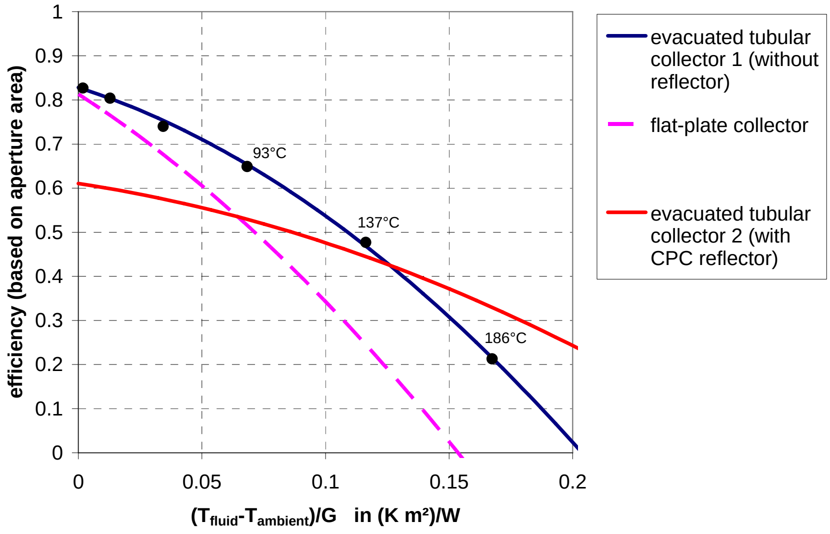


Figure 6.3. *Measured efficiency curves of three different collectors (Fraunhofer ISE measurements, highest mean collector temperatures about 185° - 190°C for all three measured curves). The dots show the efficiency points actually measured for Collector 1 and the mean collector temperature. The collector which was used for the inter-comparison tests in the Task is labeled "evacuated tube Collector 2 (with CPC reflector)".*

Reliability of collectors for industrial processes

In this final year of the Task, the work on development of medium-temperature solar collector absorbers was finalized. Suggestions for the definition of performance criteria for different medium-temperature collectors (improved flat plate collectors, stationary CPC collectors with low concentration and highly concentrating collectors) were made. The base case for comparison is a non-selective coating. Samples of absorber coatings were measured for accelerated degradation. The new suggested performance criteria were applied. The results show that the Task has now taken a first step, but more work remains to be done for further development of medium-temperature collectors.

6.4.4 Subtask D: System Integration and Demonstration

In the framework of the Task nine pilot systems were designed in close cooperation with the industry. All of the plants are installed and most of them were equipped with monitoring devices.

The following table gives an overview of the pilot systems.

Plant, Country	Application	Installed capacity Collector type	Monitoring data available
Contank, Spain	Container washing	357 kW_{th} flat plate collector	YES
ROBUR, Italy	cooling	65.5 kW_{th} (132 m²) 132 m² fresnel collector	YES
Sea water desalination, Gran Canaria, Spain	Seawater desalination	70 kW_{th} anti-reflective double glazed flat plate collector	YES
Sea Water desalination plant, Aqaba, Jordan	Sea water desalination	50.4 kW_{th} flat plate collector	YES
Fruit juices Gangl, Austria	Pasteurising bottle washing	42 kW_{th} flat plate collector	YES
Sunwash, Köflach, Austria	Car wash	30 kW_{th} flat plate collector	NO
Moguntia Spices, Austria	Cleaning and washing processes	152 kW_{th} flat plate collector	NO
Brewery Neuwirth, Austria	Brewing process	14 kW_{th} anti-reflective double glazed flat plate collector	YES
New Energy Partners, Australia	cooling	50 m² PTC	YES

Figure 6.4. Sea water desalination Gran Canaria, Spain (Fraunhofer ISE, Germany)

6.5 *REPORTS TO BE PUBLISHED IN 2008*

In general all work within Task 33/IV is completed. In 2008 the main results will be summarised by four specific booklets, dealing with the following topics:

1. Potential studies
2. Process heat collectors
3. Design guidelines for space heating of factory buildings
4. Pilot projects for solar thermal plants in industry

Furthermore a CD will be published with the following content:

- Demo version of the Pinch program PE² (energy efficiency in industrial processes)
- Matrix of industrial process indicators

The booklets will be available in a printed version and it will be available for download in pdf format from the IEA SHC web site.

6.6 *Links with industry*

The Task defined two levels of participation for the solar industry:

- **Level 1.** An industrial participant at this level was expected to participate in an annual workshop organized by SHC Task 33 and receive a visit from a Task participant at least once during the duration of the Task, and to answer technical and marketing questions on solar heat for industrial applications.
- **Level 2**. An industrial participant at this level was expected to participate in all Task meetings and to bring information and feedback from the market. Level 2 participation was seen in close connection with the main participant of the country of origin of the industry.

A total of 15 companies from Austria, Italy, Spain, Portugal, Germany, Belgium, France and Brazil participated in the Task.

MEETINGS in 2003

1st Experts Meeting

December 4th – 6th
Gleisdorf, Austria

MEETINGS IN 2004

2nd Experts Meeting

March 29 – 30
Brussels, Belgium

Third Experts Meeting

October 3rd – 5th
Oaxaca, Mexico

MEETINGS IN 2005

4th Experts Meeting

February 23rd – 25th
Madrid, Spain

5th Experts Meeting

October 3rd – 8th
Kassel, Germany

MEETINGS IN 2006

6th Experts Meeting

March 29th – 31st
Rome, Italy

7th Experts Meeting

October 11th – 13th
Lisbon, Portugal

MEETINGS IN 2007

8th Meeting

March 28th – 30th
Cologne, Germany

9th Meeting

September 10th – 12th
Graz, Austria

6.7 *Task IV National Contacts*

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Part 7: Status Report Task V: Solar Resource Knowledge Management

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7 Task V: Solar Resource Knowledge Management

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Richard Meyer
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7.1 *Nature of Work and Objectives*

The goal of the IEA 'Solar Resource Knowledge Management' Task is to provide the solar energy industry, the electricity sector, governments, and renewable energy organizations and institutions with the most suitable and accurate information on solar radiation resources on the Earth's surface. These data should be easy to access, understandable and high-quality. The scope of solar resource assessment information includes historic datasets and currently derived data products using satellite data and atmospheric modeling.

The three main objectives to be achieved in this Task are to:

- Provide further standardization and benchmarking of international solar resource datasets,
- Provide improved data reliability, availability and accessibility in formats that address specific user needs, and
- Develop methods that improve the quality and spatial and temporal coverage, with customized solar resource products, including reliable solar radiation forecasts.

Better data accessibility and standardization will shorten the time needed for planning. More accurate and more detailed information on solar irradiance helps improve solar energy system efficiency and allows it to be adapted to the irradiance characteristics of specific sites. Forecasting will increase the value and acceptance of the solar energy produced.

7.2 *Scope of the Task*

This task focuses on the development, validation, and access to solar resource information derived from satellite-based platforms, surface-based measurement stations and numerical weather models. It defines standards for intercomparison of irradiance products with respect to energy applications. Various quality control procedures for solar irradiance time series will be reviewed and possibly improved. Benchmarking of solar resource products against reference measurements will help the user to identify uncertainties better and select products which are sufficiently reliable. The Task examines the means by which the data can be made easily available to users through various web-based hosting schemes and distributed networks. Furthermore, options for forecasting solar radiation in time scales from hours to several days will be developed. Past and future climate variability of the solar resource will be studied to estimate the uncertainty of solar yields.

7.3 *Organization and Structure*

7.3.1 Collaboration with other IEA Programs

Knowledge of solar resources is highly important for any solar energy applications. Therefore, SolarPACES Task V is an IEA collaborative task along with the 'Solar Heating and Cooling' (SHC) and 'Photovoltaic Power Systems' (PVPS) Implementing Agreements. The 'Solar Resource Knowledge Management Task' is coordinated by the SHC ExCo, where it is called SHC Task 36.

7.3.2 Collaboration with other Programs

The topic covered by this IEA Task goes way beyond solar energy. It requires expertise and infrastructure from satellite remote sensing, atmospheric physics, climatology and numerical weather prediction. Therefore the Task is connected to various other international programs to share the enormous effort.

The Task collaborates with the G8 initiative, the Group on Earth Observations (GEO) Global Earth Observing System of Systems (GEOSS). Task activities form a GEO Energy Community of Practice nucleus. It covers all fields of energy, but solar energy is an ideal example of spaceborne Earth observation systems providing great benefit for planning and operation. Related to GEOSS is the European Program 'Global Monitoring of Environment and Security' (GMES). In 2007 the GMES Atmosphere Service (GAS), which includes a solar energy section, was started.

Furthermore, through NASA Langley, the IEA Task is connected to the World Meteorological Organization (WMO) Global Energy and Water Experiment (GEWEX) Program. The GEWEX 'Radiative Flux Assessment' results, especially, provide input for analysis of long-term variability of solar irradiance.

Several Task participants contribute to the UNEP (United Nations Environmental Program) Solar and Wind Energy Resource Assessment (SWERA) Program. This international program along with many national programs and Task member own contributions provide the necessary resources to conduct the common work program planned.

7.3.3 Duration

The Task began on July 1, 2005 and is planned to continue until June 30, 2010.

7.3.4 Task Structure

The Task goals will be achieved through task-sharing activities defined in a coordinated work plan. Work is carried out by participants from 19 institutions in 7 countries and the EU, as listed in Part 7.7. In 2007, additional interest came from Australia and Mexico. Significant contributions to the common work plan would be required to join. The work plan is structured in three subtasks:

7.3.5 Subtask A: Standard Qualification and Benchmarking of Solar Resource Products

The main goal of this Subtask is to ensure worldwide intercomparability and acceptance. This covers:

a) Coherence and benchmarking of models producing solar irradiance values from satellite data.
b) Accessibility and coherence of ancillary model input data such as atmospheric conditions and land-surface parameters.
c) Sensitivity analyses.
d) Ground truth validation with high-quality data.
e) Definition of validation protocols and measures of end-product confidence.
f) Cross-satellite platform and cross-model comparisons

7.3.6 Subtask B: Common Structure for Archiving and Accessing Data Products

The aim of this Subtask is to provide a user-oriented information system, such as a distributed data system, for archiving and accessing solar resource data. Key activities are:

a) Evaluate legal aspects of accessing solar resource data: This activity will establish copyright and proprietary rights for data that is to be made available through the distributed data system, and appropriate protocols with each participating institution for making the data generally available to the public. b) Identification of user requirements: this activity captures and examines needs expressed by users of the data. The outcomes are specifications for the information system, list of customers serving later as testers of the prototypes and guidance to subtask A for selection of algorithms and methods.
c) Develop data exchange protocols and metadata: Various data exchange protocols will be examined and one will be selected and documented.
d) Develop a prototype data networking procedure: A prototype web-based system will be developed whereby a user can request information of a certain type and format, and the information system provides the response or responses that most closely fulfill the request.

e) Identifying resource providers: A worldwide network of data providers will be set up, and the techniques for data exchange among the providers will be investigated.
f) User prototype testing: This activity defines a prototype that can be accessed by users, and increases awareness of the data-exchange system among external users.
g) Define automatic access by commercial applications: This activity will enable fast, automatic access of resources through the information system by using commercial applications.
h) Develop a test application 'solar micro-siting': A case study in micro-siting a solar energy system will be developed to demonstrate the benefits of the information system.

7.3.7 Subtask C: Improved Techniques for Solar Resource Characterization and Forecasting

The purpose of this Subtask is the R& D essential to improving the accuracy, and spatial and temporal resolution of current techniques. It also includes the development of solar resource forecasting products. Key activities to meet these goals are:

a) Improve satellite retrievals for solar radiation products: This activity focuses on key model input parameters and methodologies, such as cloud indices, radiative transfer schemes, aerosol data retrieval, and treatment of snow and other surface albedo artifacts. The activity also addresses ways of improving the spatial resolution of satellite-derived broadband solar resource products.

b) Climatological analysis of solar resources to ascertain future impacts on system performance due to climate variation. This activity includes analysis of long-term surface and satellite-derived datasets and climate models, specifically addressing natural long-term fluctuations associated with the ocean-atmosphere system, such as the Southern Oscillation/El Niño.

c) Forecasting of solar radiation: This activity investigates different approaches for developing solar radiation forecasts based on numerical weather predictions and extrapolation of cloud motion vectors from satellite data.

7.4 *ACTIVITIES DURING 2007*

Progress continues to be made on all aspects of Task V, although in some areas progress has been slowed due primarily to funding issues or conflicts of time by researchers. Two Task Experts Meetings were held in 2007 to discuss results achieved and coordinate next steps.

7.4.1 Task Experts Meetings & User Workshop

The Task's 3rd Task Experts Meeting was hosted by the EC Joint Research Center in Ispra, Italy from March 12th to 14th. The 4th Task Experts Meeting, hosted by SunTechnics GmbH in Ham-

Figure 7.1. Participants of the 4th Task Meeting October 2007 in Hamburg.

burg, Germany from October 23rd to 25th was followed by a user workshop. At this one-day workshop, local engineers active in all fields of solar applications from concentrating solar power and solar thermal heating and cooling to photovoltaics received an intense introduction to all main aspects of solar radiation. Much of the progress and future plans listed below were presented and discussed at the meetings. In addition, plans were made for a mid-term review to the IEA/SHC ExCo.

The next Task Experts Meeting is scheduled for June 9-10, 2008, in Austria. Various technical presentations of work achieved in the Task will be given at major conferences in the field of solar energy, satellite remote sensing and meteorology.

7.4.2 Overall Task Progress

Part of the mid-term review is based on a questionnaire filled out by a number of the task participants prior to and during the Experts Meeting. In general, the respondents showed satisfaction with the scope and progress of the subtasks and activities. Task leadership is generally viewed as competent. In many cases, progress on individual activities appears to be delayed but tolerable. In addition, funding support is generally believed to be lower than required, but also tolerable. Task technical input, as well as output, is viewed as valuable and even excellent, and task participation is mostly seen as good. Overall relevance of task output to industry is seen as good, and participation by industry is felt to be generally good. At this stage of the task, dissemination of results is only partially effective, but this is likely to improve over the next three years as more and more results are published and as the web portal becomes operational.

The U.S. released the update of its National Solar Radiation Data Base this year. The database now contains modeled solar radiation and meteorological data for over 1400 surface stations as well as seven years of 10-km resolution gridded satellite-derived solar data. The solar data are available for free, and the meteorological data are available for a fee, all from the U.S. National Climatic Data Center.

7.4.3 Specific Achievements in the Subtasks

Subtask A: Standard Qualification of Solar Resource Products

Key results of three of the four activities in this Subtask are summarized here based on discussions at the 4th Experts Meeting in Hamburg:

Activity A1:

The ground measurement datasets from the WMO 'Baseline Surface Radiation Network' (BSRN) and the 'International Daylight Measurement Programme' (IDMP) form the core for benchmarking. A common QC-procedure is under study for the ground data qualification. New input to this discussion has been provided by a CIEMAT study focusing on problems caused by incorrect time labeling and associated with DNI measurements at low sun angles. Data from ground stations that pass the common QC may supplement the BSRN and IDMP data sets for regions not covered by these data.

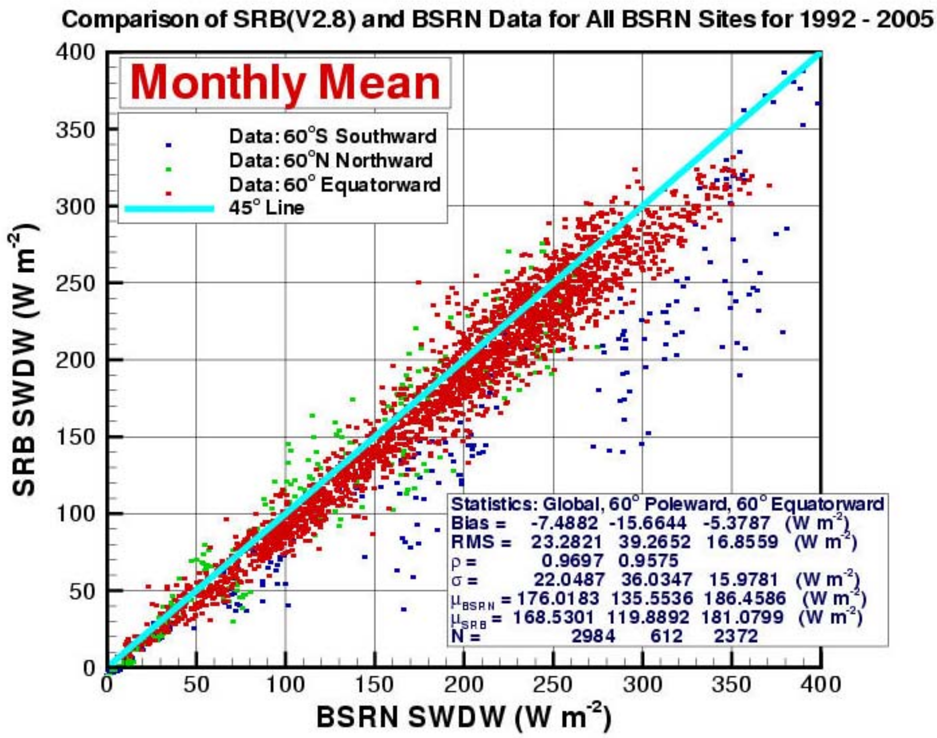

Figure 7.2. Intercomparison of the NASA Surface Radiation Budget Products for total ground irradiance versus the BSRN precesion measurements (Zhang & Stackhouse, NASA-LaRC).

Dr. Enio Pereira (of CPTEC/INPE, Brazil, a guest participant in the 4th Experts Meeting) reported on the installation of SONDA, a new high-quality (BSRN-equivalent) ground station network in Brazil. Data access is possible via the SONDA-internet portal.

A new spectroradiometer has been developed by Environment Canada to expand a reference spectral measurement database. Qualification of this spectroradiometer is ongoing.

Activity A2:

A new set of solar radiation data uncertainty measures has been defined for solar energy. Key measures are based on the Kolmogorov-Smirnov (K-S) test. These measures, which take cumulative distribution functions over representative time periods into account, are applied to satellite-based irradiance data and compared to measured ground data. First tests are demonstrated for a set of 38 German weather service stations. The results indicate complementarity of first-order measures (like mean bias, root mean square deviations) to second-order measures based on the K-S test. A paper on this method has been submitted to the *Solar Energy Journal* (Analysis of different error parameters applied to solar radiation data from satellite and German radiometric stations, by Bella Espinar, Lourdes Ramírez, Anja Drews, Hans Georg Beyer, Luis F. Zarzalejo, Jesús Polo, and Luis Martín).

Activity A3:

A case study by the University of Geneva analyzes results from the new METONORM database. A test on end-use accuracy using the performance of grid-connected PV systems has been completed. This report has been published in the *Solar Energy Journal* (Quality of performance assessment of PV-plants based on irradiation maps, A. Drews, H.G. Beyer, U. Rindelhardt).

A common structure for the presentation of first-order measures for the quality model (Mean Bias MB and Root Mean Square RMS-deviations) was agreed upon.

Two different procedures for characterization of second-order measures (matching modeled and measured distribution functions) were applied to various datasets. Both methods offer qualitatively similar results. Qualitative ranking of the procedures remains to be done.

The *European Solar Radiation Atlas* algorithm for computing irradiance on inclined surfaces was implemented as a prototype service in SoDa for application to the HelioClim-1 or –2 databases. It was recently tested against measurements made in PVPS Task 2. Preliminary results show fairly good agreement between measurements and satellite estimates. This agreement is better than observed for measurements and results from the RetScreen model. Nevertheless, it was concluded that the software should be further checked before performing more detailed analyses.

As a forerunner of the possible outcome of benchmarking taking end-use accuracy into account, intercomparison applying global horizontal irradiance products from different sources was performed for a selected region in Germany, using data for 2005. The yield of PV-systems in that region was analyzed as an end-use metric. The results were presented at the 21st European

Photovoltaic Solar Energy Conference. [Beyer, H. G., Drews, A., Rindelhardt, U. (2006): 'Irradiance maps applied for the performance assessment of PV systems - a case study for the federal state of Saxony', *21st European Photovoltaic Solar Energy Conference & Exhibition*, Dresden, Germany, 04.09. -08.09.2006]

As an example of the analysis of long-term accuracy of satellite-derived irradiance products, a study was performed using 9 years of data from a large number of radiation stations operated by the German weather service. The results have been summarized in an article submitted to *Theoretical and Applied Climatology*, [Drews, A., Lorenz, E., Hammer, A. and Heinemann, D.: 'Long-term accuracy assessment of satellite-derived global irradiance time series with respect to solar energy applications'].

Subtask B: Common Structure for Archiving, Processing, and Accessing Resource

The work plan, revised in February 2007, is being pursued in several areas. A number of accomplishments have been made that highlight work progress.

Of particular interest are successful efforts at a high political level to have the Task activities recognized by the Group for Earth Observation (GEO). A video showing four case studies in Africa exploiting solar energy achievements in solar energy systems has been made by the Ecole des Mines de Paris / Armines, with the help of NASA, JRC, DLR and the companies involved in designing the systems. This was one of the success stories presented during the GEO ministerial meeting in November 2007 in Cape Town, South Africa. The video is available at the GEO Energy Community of Practice website (http://www.geoss-ecp.org/img/video2/GEOSS-ECP.html).

The proceedings of the IEEE IGARSS international conference on Earth observation included the following communication describing the principles of the information system: Stackhouse P., Renne D., Perez R., Meyer R., Wald L., Suri M., “Towards designing an integrated Earth observation system for the provision of solar energy resource and assessment”, *Proceedings of the IEEE IGARSS Symposium*, pp. 3517-3520, July 2006.

We have received a status paper from the Bureau of Meteorology of Australia (BOM). The BOM is currently evaluating the feasibility of a new data and forecast product designed specifically for renewable energy systems and energy efficient building operation. If BOM proceeds with this and can join the Task, it will have obvious contributions to Subtask B. It should be noted that the BOM metadata in meteorology were a source of inspiration for Activity B3.

Activity B1, Evaluate the Legal Aspects of Accessing Solar Resource Data:

The purpose of Activity B1 is to produce a report outlining the information system, describing the roles and responsibilities of the participants, including legal aspects, intellectual property rights (IPR), and ethics (such as equal treatment of suppliers by a broker) in their relationships, including commercialization of data, and elements that support the belief that the outcome of Subtask B will be exploited by the solar energy community for its benefit. The document will show how IPR are taken into account in the architecture and exchange of information.

Legal aspects and property rights were analyzed in view of what is currently done in meteorology and on the web in general. ISO documentation on geographical information was taken into account. This activity is strongly linked to the design of the information system.

A first draft of this report was written at the end of March 2007, and will be updated during the course of this IEA Task. Discussions are held in workshops or meetings with potential providers, including companies, to accumulate case studies and experience. The issue of a typical service agreement will be studied based on this material.

Extensive knowledge about IPR for meteorological and satellite data in the European Union has been acquired by the Task. A case in point is "public" data (e.g., from NASA or BOM) sold by third parties. Effective SoDa Service and NASA-SSE database links and combination of the NASA-SSE database (free access) with the HelioClim database (paid access) have been established. Access to these integrated services is now free.

Activity B2, Identification of User Requirements:

This activity captures and examines needs expressed by users of the data. The outcome provides specifications for the information system, a list of customers who will later serve as prototypes testers and guidance in the selection of algorithms and methods for Subtask A.

The user survey was taken using a questionnaire. Feedback from information systems managers (NASA-SSE, PV-GIS, Satel-Light, SoDa, etc.) was also taken into account. A server at JRC hosted the online questionnaire through February 2007. Several relevant servers pointed to the JRC to create awareness and increase the number of responses. Approximately 110 answers were collected. Analysis was performed by the JRC (Thomas Huld). The survey reveals several interesting features that have been documented in a report. The document is now in its final form, available and published on the Task 36 website. This completes Activity B2.

Activity B3, Develop Data Exchange Protocols and Meta-Data:

This activity includes close monitoring of standardization procedures, investigation of available tools, their limits and advantages, and participation in international working groups, such as INSPIRE (Europe) and GEOSS.

There are several levels in exchange protocols. The information system relies on the most standard at the lowest levels. An example is the HTTP protocol commonly used to browse the Internet. These protocols are embedded in a satisfactory manner in the middleware tools selected in Activity B4 in spring of 2007 (JBoss, open source). These issues should be considered as handled completely by middleware with no need for development or augmentation.

During this reporting period, activities have concentrated on the exchange protocol at a semantic level (i.e., the "solar radiation" level). Information should be depicted by metadata in a thesaurus, which should have a practical implementation on a computer, called an application schema or XML schema, since such schemes are often written in XML. We analyzed ISO (International Standard Organization) and CEN (Commitée Européen de Normalisation), OGC (Open GIS Consortium), INSPIRE (Infrastructure for Spatial Information in the European Community), and WMO metadata standards, looking for metadata implementation schema (XML schemes) for meteorology and geospatial information.

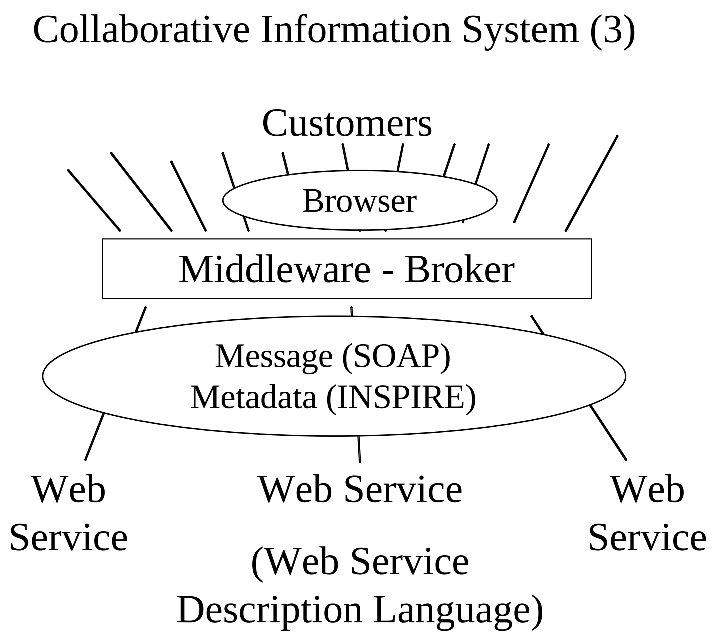

Figure 7.3. Structure for a collaborative information system for the distribution of solar resource products.

As the choice of metadata and the data structure have a strong impact on the system architecture and its functionalities, we also paid close attention to information exchange between the middleware and a web service. A standard, called WSDL (Web Service Description Language) was adopted. After a search and testing several tools, Armines has selected the open-source Eclipse workshop to enable efficient exploitation of these schemes for developing and deploying web services.

We also took SoDa Service experience in web service composition into account. Though an efficient automatic and adaptive composition system is beyond the scope of this IEA Task, we took this functionality into consideration in our analysis of the schemes proposed. In particular, we had to understand WSDL limitations in invoking a web service.

Considering all these elements together, the conclusion was that none of the schemes is suited for the management of irradiance time series, one of the products most in demand by users. We have therefore developed a specific thesaurus for solar irradiance time series. The proposed scheme takes the intellectual property rights of the providers into account. This thesaurus has been sent to the INSPIRE Implementation Group for comments and has been presented at an international conference (Gschwind Benoît, Lionel Ménard, Thierry Ranchin, Lucien Wald, Paul Stackhouse, 2007, "A proposal for a thesaurus for web services in solar radiation", in *Proceedings EnviroInfo* 2007, O. Hryniewicz, J. Studzinski and M. Romaniuk (Eds), Shaker, vol. 1, pp. 135-142.).

As this standardization domain is very prominent at this time, we made an effort to be involved in such activities in order to be aware of the outcomes and to raise awareness about our concerns in solar energy (e.g., management of time systems, composition of services). We have particularly registered the SoDa Service as an SDIC (Spatial Data Infrastructure Community) with the INSPIRE community and the three candidate GEOSS portals: ESA, OGC and ESRI. In this case, the SoDa Service will serve as a proxy for the future Task information system.

Activity B4, Develop Prototype:

A prototype web-based system will be developed whereby a user can request information of a certain type and format, and the information system provides the response or responses that most closely meet the request.

Prototype development is ongoing. A first version is presently available (http://project.mesor.org). This prototype is a proof-of-concept as it implements all elements discussed above (web service installed on another web server, thesaurus, exchange protocols, etc.).

In order to ensure that developments are state-of-the-art, Armines and NASA participate in the GEOSS group on System Architecture. We found that this group is promoting the JBoss middleware and the LifeRay portal that we selected in Spring 2007, which enforces the confidence we have in these open source tools and their developer communities.

Revision of the PV-GIS web by the JRC in the past months offered an opportunity to evaluate practical solutions for the selection of a given geographical site (Google tools). Meteotest has already exploited these tools for the product MeteoNorm. They have therefore been adopted in the prototype. Of interest to the GUI (graphical user interface) is the open source tool 'Ajax'. Analysis is ongoing.

The "Use Cases" are under development. They show how the information system is employed by users. This is done in close cooperation with Activities B3, Architecture Design, B4, Prototype Development and B5, Service Providers, taking into account user needs expressed and the experience of existing information systems managers.

As previously discussed, the composition of the web services was identified as a weak point in our case. The composition defines a plan for calling services. Armines is working on composition concepts, which can range from fully manual (the case of the SoDa Service) to fully automatic. Except the manual case, all other concepts are relevant to RTD activities that are beyond the scope of the Task. However, as the SoDa Service offers an excellent opportunity for testing real cases, these research activities at the Ecole des Mines de Paris are closely linked and may therefore benefit the Task. A test bed comprised of 16 scenarios, or user cases, has been devised that can be instantiated by services dealing with irradiance or temperature. This test bed will enable composition prototypes to be tested. The test bed was presented at an international conference: Gschwind Benoît, Lucien Wald, Robert Mahl, François Irigoin, Lionel Ménard, 2007, "Test of several approaches for the composition of web services in meteorology", in *Proceedings EnviroInfo* 2007, O. Hryniewicz, J. Studzinski and M. Romaniuk (Eds), Shaker, vol. 1, pp. 127-134".

Activity B5, Develop Network of Resource Providers:

This activity aims at establishing a worldwide network of data providers (through web services). Two different approaches were adopted during the reporting period. The first one is to proceed as planned with the analysis of available techniques for data exchange between the web services and middleware, including their adoption and possible augmentation. The second approach exploits opportunities to connect new web services to the SoDa Service. In that case, the SoDa Service serves as a proxy for the information system. The second approach permits quick and efficient development of new services, having them tested by a large number of customers very rapidly and finally, acquainting the provider better with the proposed collaborative system.

Exchange techniques between middleware and web services are based on the WSDL and SOAP protocols. As discussed earlier, the Eclipse tool (open source) for exploiting the thesauri and creating the web service is recommended. A first draft of a "how-to" document for the attention of web service developers has been written and has been sent to partners for comments.

Several providers in the SoDa Service and others (e.g. Armines, ENTPE, JRC, Meteotest, NASA) have stated their interest in offering their services in the new information system and show a high level of knowledge on information technologies. This supports our expectation for rapid population of the system by services.

Regarding the second approach, an effort was made, under the IEA - GEOSS umbrella, to connect NASA's SSE database to the SoDa Service. In addition, a compound service was made that jointly exploits the SSE and HelioClim (Armines) databases and selects the information having the best spatial resolution. Since these two new services in SoDa have become available, a large number of requests have been made (more than 1500 anticipated from July to December 2007), clearly demonstrating the usefulness of such services.

Armines has revised a web service available through the SoDa Service that allows companies to create ASCII files that can be entered into GIS software for producing irradiance maps (a common requirement specified by users). Here again, the rapid prototyping facility offered by the SoDa Service proves its efficiency. After a few months of testing, the service was revised for its GUI for outputs and an asynchronous capability was added. This functionality should exist in the final system developed.

The possibility of the SoDa Service accessing the information held on the SWERA web site was analyzed. This is not currently possible at a low enough cost.

Activity B6, Define Automatic Access by Commercial Applications:

This activity will enable fast automatic access to resources by the information system through the use of commercial applications.

Though the activity has not formally begun, there are already some preliminary results. A web service was developed by Armines to automatically connect to NCAR / NCEP forecasts, which are thereby offered on the SoDa Service. This connection worked for several months with a growing number of users, but has not been working properly since September 2007. A possible solution is the introduction of asynchronous capability. It is still unclear whether the solution adopted in the case above (see Activity B5) is the most appropriate given user expectations.

Activity B8, Example application using solar micro-siting in GIS:

This activity will be implemented from month 48 to month 60, i.e., the last year of the current Task 36 work plan. Currently, only limited resources have been secured for this activity 2 FTE-months vs. 17 FTE-months recommended), raising concerns about the viability of this activity. This should be discussed at the next Task 36 Experts Meeting.

Subtask C: Improved Techniques for Solar Resource Characterization and Forecasting

Activity C.1: Improving Satellite Methods for Solar Radiation Products:

NASA/LaRC and SUNY/A showed the use of sub-grid variability to increase resolution of long-term data products) (Perez et al.).

Activity C.2: Climatological Analysis of Solar Resources:

NASA/LaRC reprocessed SSE Release 6.0. These results,

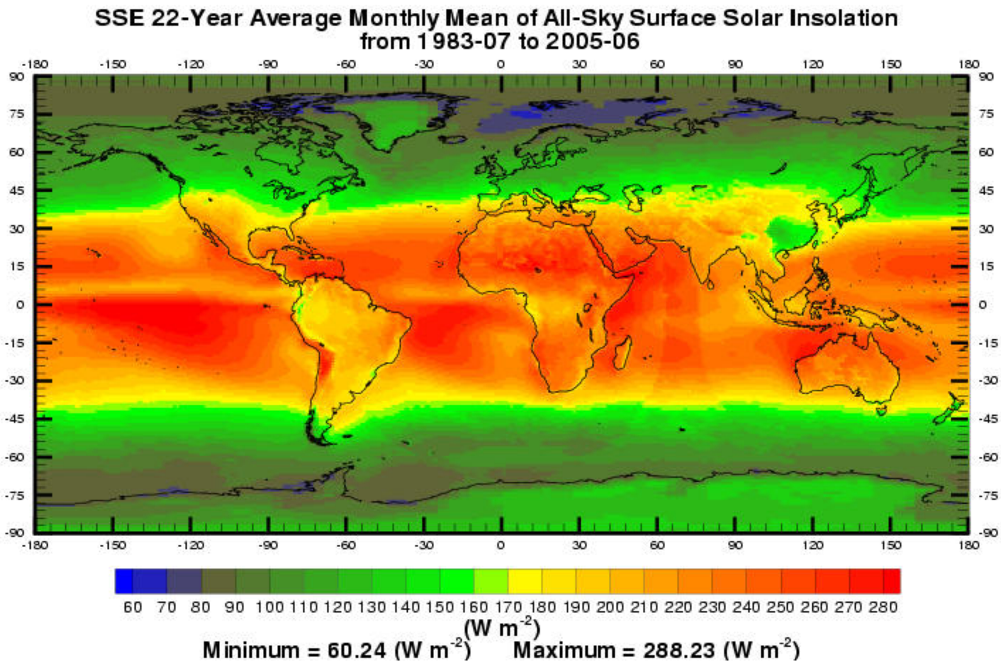

Figure 7.4. Long-term average solar irradiance from NASA satellite dataset (Stackhouse et al., 2007).

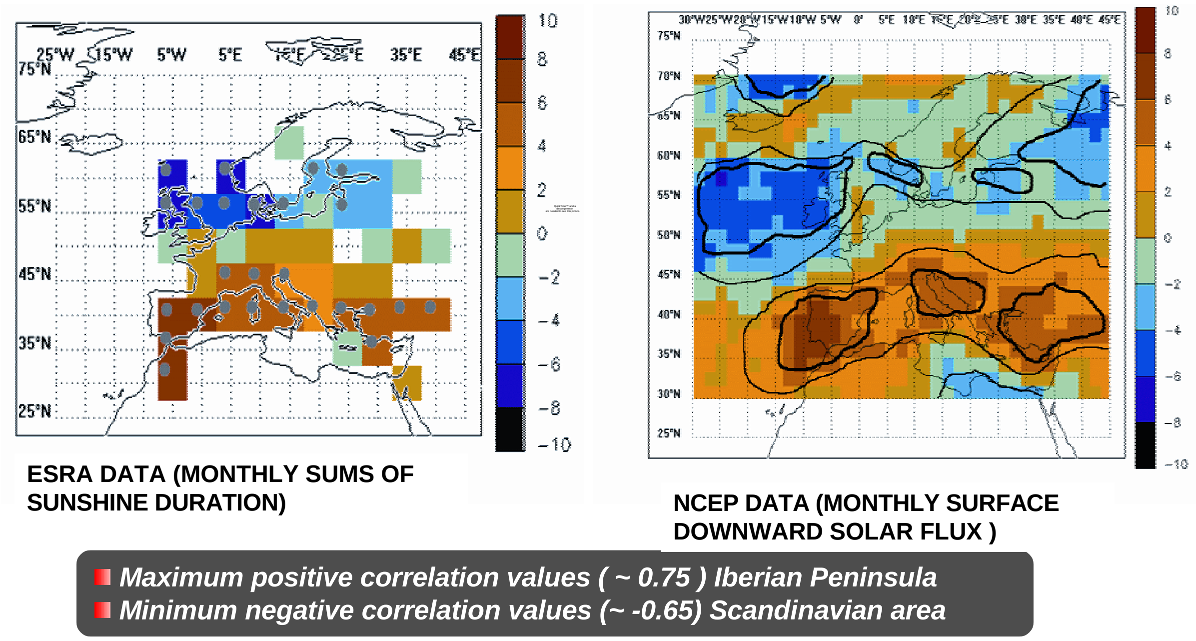

Figure 7.5. Influence of the North Atlantic Oscillation (NAO) on solar irradiance over Europe.

based on more than 20 years of data, improved solar irradiance maps.

Activity C3: Evaluate Solar Radiation Forecasting Procedures

The participants involved in this activity have preformed continuing evaluation and further development of the different forecasting algorithms. Their results have been presented at several conferences.

Forecast processing for benchmarking forecast algorithms has started. SUNY Albany, Meteotest, Meteocontrol, Oldenburg University, DLR –DFD, Blue Sky Wetteranalysen and CIEMAT are contributing forecasts for intercomparison.

SUNY/A completed forecast processing for benchmarking for the USA; test period: 4/07 - 9/07

DLR-DFD evaluated EURAD MADE system aerosol and cloud forecasts for improved forecasting of clear-sky irradiances over the European Centre for Medium-Range Weather Forecasting (ECMWF) forecasts. Results were presented at the DACH 2007, 10-14 September 2007, Hamburg, Germany. The use of irradiance forecasts for managing solar thermal power plants was studied in cooperation with DLR-TT.

At Oldenburg University, cloud forecast analysis using the ECMWF global model with respect to irradiance forecasts to derive an enhanced irradiance forecast was continued. An approach to provide confidence intervals for PV power forecasts was developed and included in a paper on solar power prediction, presented at the 20th European PV Conference (Lorenz E., Heinemann D., Wickramarathne H., Beyer H.G., Bofinger S. (2007): *Forecast of ensemble power production by grid-connected PV systems*. 20th European PV Conference, 3.9-7.9 2007, Milano, Italy). Furthermore, a paper on solar power prediction has been presented at the DACH 2007, 10-14 September 2007, Hamburg, Germany.

An analysis of irradiance predictions based on the WRF mesoscale model processed at the ForWind Institute, Oldenburg University Center of Wind Energy Research and Hanover University, was performed as a joint Oldenburg University-CIEMAT project.

At Meteotest, irradiance forecasts based on the MM5 model and GFS input data have been operationally processed and evaluated since June 2006.

CIEMAT has performed an analysis of ECMWF irradiance reanalysis data. The evaluation was done for Spanish radiometric stations operated by the Spanish National Weather Service (INM) for the period 1994-2003.

Bluesky Wetteranalysen began to process operational irradiance forecasts in July 2007.

7.5 *Work Planned for 2008*

7.5.1 Subtask A: Standard Qualification of Solar Resource Products

Hochschule Magdeberg (H2M) and CIEMAT will continue comparison of procedures for definition of measures.

7.5.2 Subtask B: Common Structure for Archiving, Processing, and Accessing Resource

Activity B1 will accumulate case studies and experiences regarding web-based data dissemination. We will analyze U.S. law on the usage of data delivered by NASA and NREL, and discuss similar issues with the Australian BOM. We will also proceed with the system description report.

Activity B3. The thesaurus and related schema are critical to a collaborative web-based information system. Though already implemented and available, the proposed schemes will be presented and discussed in the forthcoming months at various meetings and workshops to raise awareness of our effort and if possible, establish it as a de facto standard for radiation data. The thesaurus will need to be extended to meteorological data time series, including temperature and humidity (see user requirements).

A new language and thesaurus should be developed for additional service descriptions allowing task outputs specific to our system: IPR, GUI, (presentation, format). This will be done following the “use-cases” in close cooperation with Activities B3, B4 and B5 (service providers), taking into account user needs expressed and existing information system manager experience.

We will create new thesauri for other products, such as statistics on types of days, to facilitate service provision.

We will proceed with participation in international activities on standardization of data products, and will set up documentation for these thesauri. The thesauri will be put on a web server with public access.

Activity B4. We will proceed with prototype development following the use cases, with emphasis on the GUI and information exchange between middleware and a web service. We will also prepare user prototype assessments.

Activity B5. We will proceed with development of services, with two major goals, better exploitation of the NASA/SSE database and assisting other web service providers.

Activity B6. Though not officially started, we will investigate automatic prototype connection to NCEP / NCAR forecasts to check prototype capability.

7.5.3 Subtask C: Improved Techniques

Activity C3: Evaluate Solar Radiation Forecasting Procedures

Task participants will continue evaluation and further development of forecasting algorithms.

Benchmarking for the USA for the April–September 2007 period will be completed during the next reporting period and a technical paper on the results will be prepared. SUNY/A, Meteotest, and Oldenburg University will contribute to this intercomparison.

Forecast processing for European benchmarking for the July 2007 to June 2008 period will be continued.

Three new irradiance forecasting projects will start:

- Development of energy management of a solar thermal heating power plant using ASiC solar irradiance forecasting
- Natural Resources Canada and the Canadian Meteorological Centre (Environment Canada) joint project on solar and PV forecasting
- The new participant, University of Jaen in Spain, will work on solar radiation evaluation and forecasting using NWP models.

7.6 *Task V National Contacts*

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Part 8: Status Report Task VI: Solar Energy and Water Processes and Applications (SEWPA)

Operating Agent:
Julián Blanco
Plataforma Solar de Almería. CIEMAT

8 Task VI: Solar Energy and Water Processes and Applications

Operating Agent: Julián Blanco Gálvez ((E))
julian.blanco@psa.es *

8.1 Nature of Work & Objectives

In 2007, a new SolarPACES Task called "Solar Energy and Water Processes and Applications" was created, mainly for the purpose of providing the solar energy industry, 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 processing, replacing the use of conventional energies.

The need for development of this specific area of solar energy arises from the serious water problems expected in many areas of the world during the coming decades. With the added prospects of increasing energy costs, it makes good sense to seriously consider the use of solar energy to solve or palliate water problems. Specific technological development will be required for this.

The scope of work covers all solar radiation technologies supplying either thermal or photon primary energy to a water treatment process. In other words, any water treatment in which solar energy can be used in the place of other conventional energy resources. Specific processes and applications included in the scope of the Task are the following:

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- Brackish and seawater desalination: Any technical procedure or methodology for reducing or removing the salt content from water.
- 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 this Task is to improve the conditions for market introduction of solar water treatments and solve water problems at locations with abundant solar energy resources, while contributing to reduced fossil-fuel consumption. The main specific focus of the activities and initiatives addressed is to demonstrate the potential of solar energy for water applications.

In 2007, this new Task was presented at the following major international conferences:

- European Desalination Society Conference on Desalination and the Environment. Halkidiki Greece. April 22-25, 2007.
- Third International Conference on Desalination Technologies and Water Reuse - ADST 2007. Sharm El-Sheikh, Egypt. May 7 - 8, 2007.

8.2 Status of Technology

Research in Task VI is classified according to the abovementioned goal into the following three domains or subtasks:

- Subtask VI.1. CONCENTRATED SOLAR POWER AND DESALINATION PLANTS. The objectives of this Subtask are to: i) collect existing knowledge and experience on hybrid power and desalination plants for application to MW-size hybrid solar power desalination plants; ii) analyze and determine the main technological characteristics of hybrid solar power and desalination plants; iii) promote collaborative initiatives in specific assessment of 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 this knowledge among main stakeholders: solar manufacturers, process engineers, associated industry, installers and potential customers and users; iii) promote collaborative initiatives for specific assessment of the technical and economic feasibility of the most appropriate and promising technologies

- Subtask VI.3. SOLAR WATER DETOXIFICATION AND DISINFECTION SYSTEMS. The objectives 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, including evaluation of 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 technical and economic feasibility of specific water detoxification and disinfection problems, also identifying potential follow-up demonstration case studies.

Current ongoing Task VI activities are presented in Table 8.1, following the previous structure. In the sharing column, “I” refers to information sharing; “M” to task sharing by member countries, “T” to task sharing through SolarPACES; and “C” to cost sharing. The main SolarPACES contact person is indicated.

Table 8.1. Summarized Task VI reported activities organized by Sector

Sectors and Activities	Contact	*Sharing*			
		I	**M**	**T**	**C**
Sector 1. Concentrated Solar Power & Desalination Plants					
AQUA-CSP	F. Trieb		x		
CSPD-COMISJO	M. Schmitz		x		
Sector 2. Solar Thermal Desalination Systems					
MEDESOL	J. Blanco		x		
POWERSOL	J. Blanco		x		
Sector 3. Solar water detoxification and disinfection					
SOWARLA 1+2	C. Jung	x			
INNOWATECH	W. Gernjak		x		
TRAGUA	B. Sánchez	x			
PHOTONANOTECH	S. Malato		x		
SODISWATER	P. Fernández		x		
DETOX-H2S	B. Sánchez	x			
Preparation of highly efficient photocatalytic materials	B. Sánchez	x			

The most important achievements in 2007 with up-to-date information about project participation, objectives, status, and relevant publications, are summarized below.

8.2.1 Concentrated Solar Power and Desalination Plants

AQUA-CSP – Concentrating Solar Power for Seawater Desalination

Participants: Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR)(D); National Energy Research Center (NERC) (JOR); Univ. Aden (YEM); Univ. Sana'a (YEM); Univ. Bahrain, (BHR); Prof. Abdelaziz Bennouna, (Rabbat, MRC); Internationales Forschungszentrum für Erneuerbare Energien e.V. (IFEED)(D); Kernenergien – The Solar Power Company (D); Nokraschy Engineering GmbH (NL, D, EGY); Deutsche Gesellschaft Club of Rome (CoR) (D); House of Water and Environment Palestine (HWE, Palestine); Center for Solar Energy Studies (CSES) (LBY) Centre de Développement des Energies Renouvelables (CDER, MRC); Univ. Bremen (D)

Contact: Franz Trieb, DLR, franz.trieb@dlr.de

Funding: German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety: 195 k€

Duration: June 1, 2006 – December 31, 2007

Background: The AQUA-CSP study analyses the potential for concentrating solar thermal seawater desalination in the Middle East and North Africa (MENA). The study will provide a comprehensive data base on technology options, water demand and water deficits, water resources, solar energy resources and the potential markets for solar powered desalination in the MENA countries.

Objectives: The AQUA-CSP study provides a first information base for the political framework that is required for the initiation and realization of such a scheme. It quantifies the available solar energy resources and the expected cost of solar electricity and water, a MENA water sector integration scenario for 2050, and shows the environmental and socio-economic impacts of the wide dissemination of this concept.

Achievements in 2007: The study has been completed and is downloadable at www.dlr.de/tt/aqua-csp. A long-term scenario for the year 2050 for each of the twenty countries analyzed evaluates the socioeconomic and environmental impact that would result from wide dissemination of the concept in the MENA region.

Publications: [8.1] - [8.8]

CSPD-COMISJO – Concentrated Solar Power and Desalination for Communities in Israel and Jordan

<u>Participants:</u> Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR); Ben Gurion Univ. of the Negev (IL); National Energy Research Center (NERC) (JOR); Univ. Bremen (D)

<u>Contact:</u> Mark Schmitz, mark.schmitz@dlr.de

<u>Funding:</u> German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety: 429k€

<u>Duration:</u> May 1, 2007 - April 31, 2010

<u>Background:</u> The entire Middle East has high solar irradiation and a pressing need for fresh water. The optimal layout for a medium-scale solar desalination unit will be found for two sites in Israel and one in Jordan. DNI will be measured at the sites and correlated with satellite data for long-range data and a high time resolution for future dynamic analyses.

<u>Objectives:</u> The aim of the project is to screen potential combinations of solar energy conversion technologies for heat or electricity with compatible desalination approaches.

<u>Achievements in 2007:</u> The most promising concept for a site close to the Dead Sea; detailed are planned to analyze the economic potential of the chosen solar desalination concept.

<u>Publications:</u> No publications are yet available

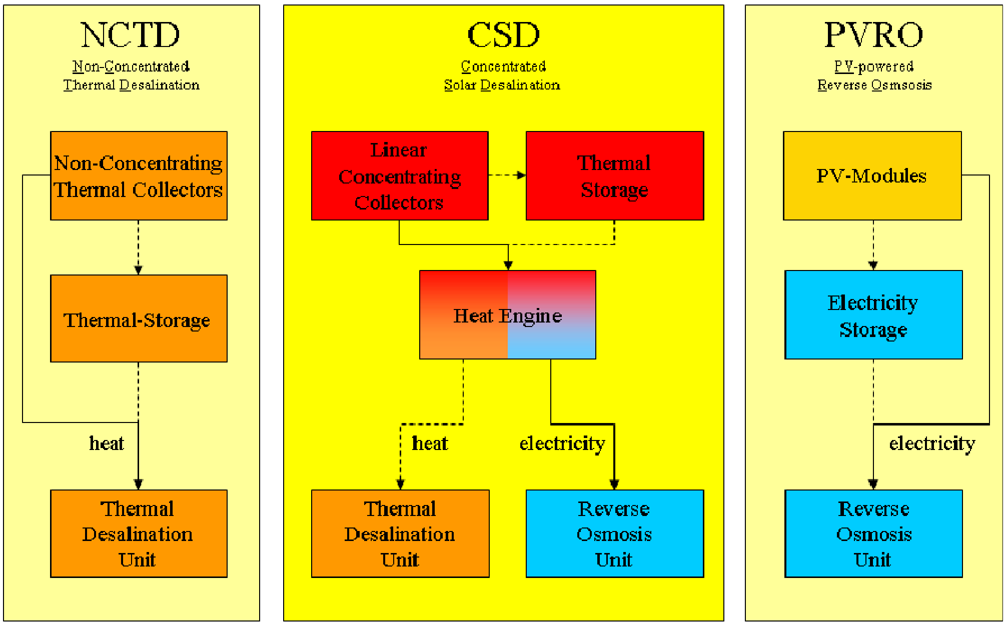

Figure 8.1 Principal solar desalination systems under investigation with emphasis on CSP+D.

8.2.2 Solar Thermal Desalination Systems

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

Participants: CIEMAT (E); Univ. La Laguna (E); Acciona Infraestructuras (E); ACUAMED (E); AOSOL (P); Univ. Stuttgart, (D); Tinep (MEX); National Autonomous Univ. Mexico (MEX); Royal Institute of Technology (S); Scarab AB, (S); Iberinsa (E).

Contact: Julian Blanco, PSA-CIEMAT, julian.blanco@psa.es

Funding: EC-funded project, cost-shared: 1,385 k€

Duration: October 1, 2006 - September 30, 2009

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

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

Figure 8.2 Overview of MEDESOL-1 prototype (solar field and membrane distillation units not visible).

Achievements in 2007: (i) Development of a new solar collector based on compound parabolic collector technology; (ii) development of non-fouling heat exchanger surfaces; (iii) a first complete experimental system (MEDESOL-1) has been set up to test new components and system concepts in 2008.

Publications: [8.9]

POWERSOL – Mechanical Power Generation Based on Solar Thermodynamic Engines

Participants: CIEMAT, (E); Univ. La Laguna, (E); Instituto de Engenharia Mecanica, (P); Ao Sol, (P); ETH, (CH); Ecosystem Environmental Services, (E); INETI, (P); École Nationale d'Ingénieurs de Tunis (TUN); Ain Shams Univ., (EGY); Lotus Solar Technologies,; Alternative Energy Systems, Tunisia; Suez Canal Univ., (EGY); Univ. Ouargla, (ALG); Univ. Seville, (E).

Contact: Julián Blanco, PSA-CIEMAT, julian.blanco@psa.es; Lourdes García, Univ. Seville, lourdesg@esi.us.es

Funding: EC funded project, cost shared (FP6): 1,050 k€

Duration: January 1, 2007 - December 31, 2009

Background: The project focuses on the technological development of solar-thermal-driven mechanical power generation based on a solar-heated thermodynamic cycle. Mechanical energy could be either used directly for electricity generation (using a generator) or for brackish or seawater desalination by coupling the output to a high-pressure pump connected to a conventional reverse osmosis system

Objectives: The main project objective is the development of environmentally-friendly improved-cost shaft power generation based on solar thermal energy, optimized for supplying the basic demands of rural or small communities.

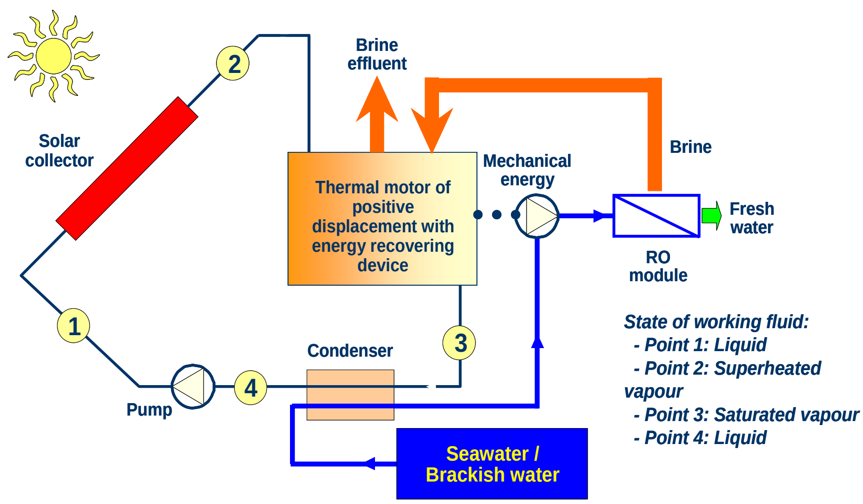

Figure 8.3 Schematic diagram of a desalination application of proposed POWERSOL technology

Achievements in 2007: During this period, potential working fluids and cycles were reviewed and the preliminary design features of the technology to be developed were selected. This initial design was enough for full simulation of the power cycles selected.

Publications: [8.10]-[8.16]

8.2.3 Solar water detoxification and disinfection systems

SOWARLA 1+2 - Solar Water Treatment for the DLR Site Lampoldshausen

Participants: Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Hirschmann Laborgeräte GmbH, KACO Gerätetechnik GmbH (D)

Contact: Christian Jung, DLR, christian.jung@dlr.de

Funding: Deutsche Bundesstiftung Umwelt (DBU): 779 k€

Duration: April 1, 2005 – February 29, 2008

Background: Solar photocatalytic water treatment is a promising technology for commercial application since many R&D projects and a number of demonstrations have shown its potential. What are still lacking are commercially available solar reactors. Therefore, two German companies, Kaco Gerätetechnik GmbH and Hirschmann Laborgeräte GmbH, along with the DLR have formed a consortium to develop a market-ready solar reactor.

Objectives: In this project, a new type of non-concentrating tubular receiver (NCTR) will be designed for solar photocatalytic applications. The NCTR receiver consists mainly of borosilicate-glass tubes in a compact arrangement with no reflective material. Only cheap, simple rugged parts are used for the construction of the NCTR receiver and support structure to enhance the cost-effectiveness and weather resistance of the receiver system.

Wastewater from the DLR rocket engine test facilities in Lampoldshausen, Germany, was used as a model for industrial application. A pilot plant will demonstrate NCTR capability. In a third phase planned for 2008, a demonstration plant able to treat all of the wastewater from the DLR Lampoldshausen center will be built.

Achievements in 2007: Comparative detoxification tests were done with a pre-pilot reactor using heterogeneous and homogenous photocatalysis for the detoxification of artificial wastewater containing cyanide or hydrazine. Based on the results, a NCTR pilot plant was installed for the treatment of wastewaters containing hydrazine from the rocket test facilities at DLR site Lampoldshausen (Figure 8.4). The NCTR pilot plant consists of a

32-m² NCTR receiver and a pumping unit for 1-m³ batch processing of rocket test facility wastewater. The pilot plant was tested successfully.

Publications: No publications are yet available. A paper will be presented at the 14th SolarPACES Symposium in 2008.

Figure 8.4 SOWARLA Prototype reactor, Lampoldshausen Germany.

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

Participants: CNR - Istituto di Ricerca Sulle Acque (I), Aachen Univ. Technol. (D), Tech. Univ. Delft (NL), Swedish Env. Res. Inst. Ltd (S), Cranfield Univ. (UK), Swiss Fed. Inst. Tech. (CH), CIEMAT-PSA (E), Norw. Inst. Wat. Res. (N), SolSep BV (NL), Bayer MaterialScience AG (D), ITT Wedeco (D), Austep S.r.l. (I), Albaida S.A. (E), AnoxKaldnes (S), Water Innovate Ltd (UK), DHV (NL), Adv. Wastewater Manag. Centre (AUS).

Contact: Dr. Antonio López, CNR-IRSA, antonio.lopez@ba.irsa.cnr.it; Dr. Wolfgang Gernjak, CIEMAT-PSA, wolfgang.gernjak@psa.es

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

Duration: November 1, 2006 – October 31, 2009

Background: New concepts and processes in industrial wastewater treatment with great potential benefits for the stable effluent quality, for savings in energy and operating costs, and for the protection of the environment, in keeping with the goal of the EU Environmental Technologies Action Plan.

Objectives: Development of aerobic granulation bioreactors; coupling of Advanced Biotreatment and Advanced Oxidation Processes; new membrane processes; Life Cycle Assessments and Costing. The CIEMAT is focusing on further development of solar photo-Fenton treatment for coupling with aerobic biological treatment.

Achievements in 2007: During 2007, the CIEMAT-PSA treated industrial pharmaceutical wastewater by solar photo-Fenton technology. Wastewater biodegradability was studied during the chemical oxidative treatment to determine the point when treated wastewater can be discharged into a biological treatment plant. Figure 8.5 shows a degradation curve on which the point where biodegradability was reached is marked.
A biological treatment plant was also designed to be installed at Albaida S.A., a local company and project partner, which treats the wastewater from the washing of pesticide containers. This company currently applies solar photo-Fenton treatment alone and the aim is to upgrade the treatment to improve performance, plant capacity and lower treatment costs.

Publications: [8.17]-[8.19]

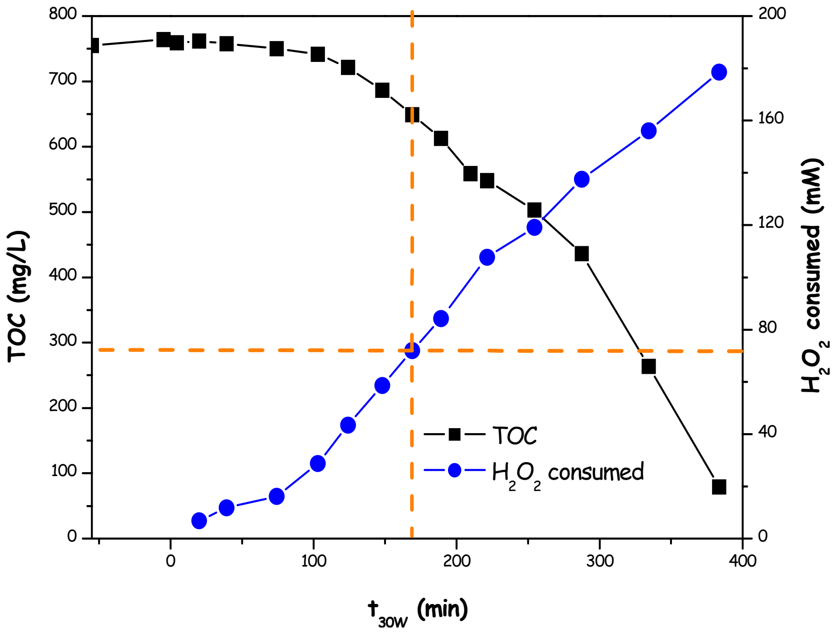

Figure 8.5 Degradation of saline pharmaceutical wastwater from nalidixic acid production in CPC solar collectors with photo-Fenton (cFe = 20 mg/L).

TRAGUA– Treatment and Reuse of Wastewaters for Sustainable Management

Participants: Up to 24 Spanish Public Institutions and Companies

Contact: Benigno Sánchez, CIEMAT-PSA, benigno.sanchez@ciemat.es; Sixto Malato Rodríguez, CIEMAT-PSA, sixto.malato@psa.es

Funding: Spanish Ministry of Education and Science (National R&D Programme): 4,900 k€.

Duration: January 1, 2006 – December 31, 2011

Background: Spain is the European country with the highest water deficit and only 5% of wastewater is reused. The reasons so little water is reused are diverse, the most important among them being the lack of treatment protocols for treated water from municipal wastewater treatment plants (MWTP) and the lack of clear criteria for choosing technologies.

Objectives: A five-year project (2006-2011) for increasing wastewater reuse in Spain. When finished, the program will provide an inventory of wastewater for potential reuse, treatment protocols according to their characteristics, and economically improved technologies available, standard methods of chemi-

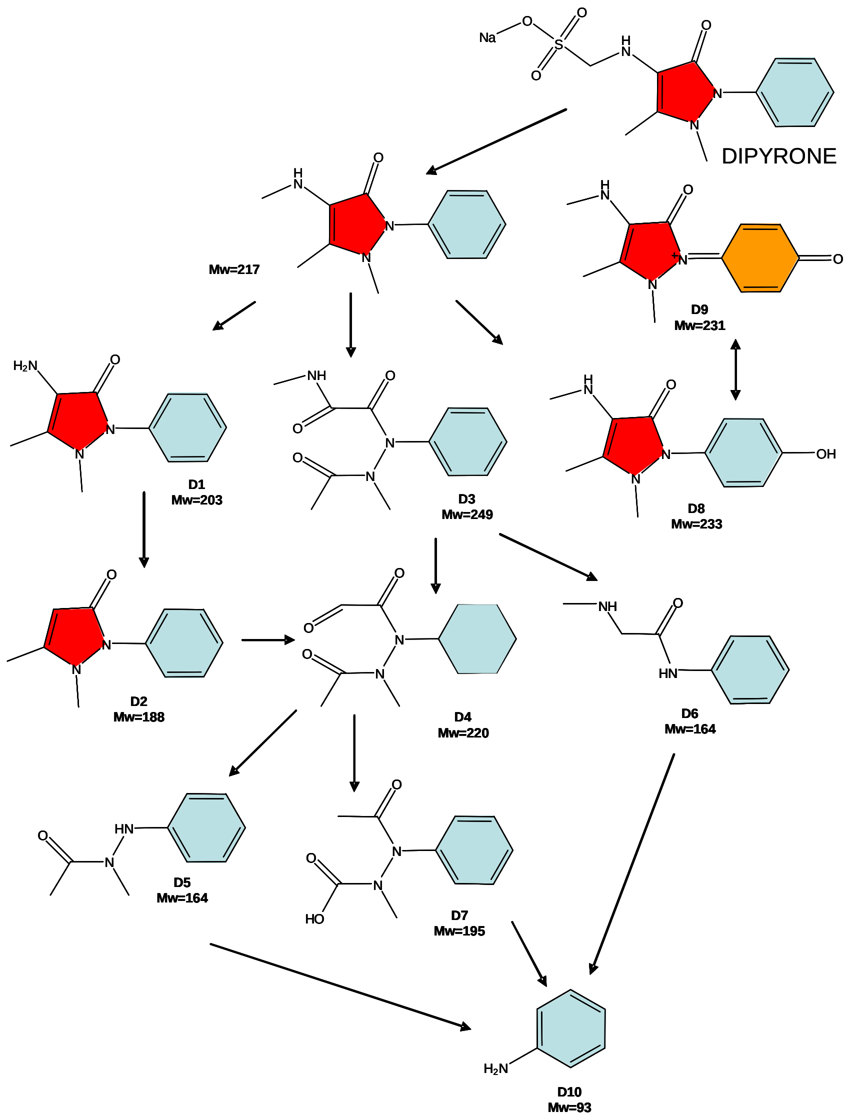

Figure 8.6 Dipyrone (antipyretic drugs usually found in MWTP) degradation pathway during solar photo-Fenton treatment

cal, microbiological and toxicological analysis, information about the impact of water on the environment and the respective socio-economic analyses.

Achievements in 2007: Main achievements in 2007 were the establishment of analytical, toxicological and disinfection protocols for evaluating the different treatment processes. First steps for demonstrating solar photo-Fenton as a final sewage plant treatment.

Publications: [8.20], [8.21]

PHOTONANOTECH- Application of Photozyme Nanoparticles for Water Purification, Textile Finishing and Bleaching and Photodynamic Biomineralization

Participants: Sofia Univ. (coordinator, Bulgaria); CIEMAT-PSA (E); Univer. Politécnica de Cataluña (E); Univ. Minho (P); Technical Univ. Kaiserslautern (D); Politecnico di Torino (I); Specialni polimeri Ltd. (BUL); Tinfer (E); Colorcenter (E); Tecnologie Biomediche S.r.l. (I)

Contact: Prof. G. S. Georgiev, ohtgg@chem.uni-sofia.bg; Sixto Malato Rodríguez (CIEMAT-PSA), sixto.malato@psa.es

Funding: EC funded project, cost shared: 2,450 k€

Duration: April 1, 2007 – March 31, 2010

Background: A three-year project (2007-2010) for enhancing use of photozymes. Photozymes are amphiphilic water-soluble copolymers consisting of hydrophobic chromophoric and hydrophilic monomer units forming nano-sized pseudo-micelles with a hydrophobic core enabling them to convert the solar energy into chemical energy through an antenna effect with singlet oxygen production and the tailored photochemical transformation of solubilizates in the hydrophobic pocket molecules. The co-existence of these two distinctive photosynthesis effects opens a wide range of possible innovative technological developments.

Objectives: To develop new photozymes and investigate their long-term potential innovation as: (i) photocatalysts in solar wastewater detoxification and disinfection; (ii) textile finishing agents; (iii) a new approach to control the biomineralization process (photodynamic biomineralization); (iv) new biomedical coatings and materials with suppressed inflammatory response.

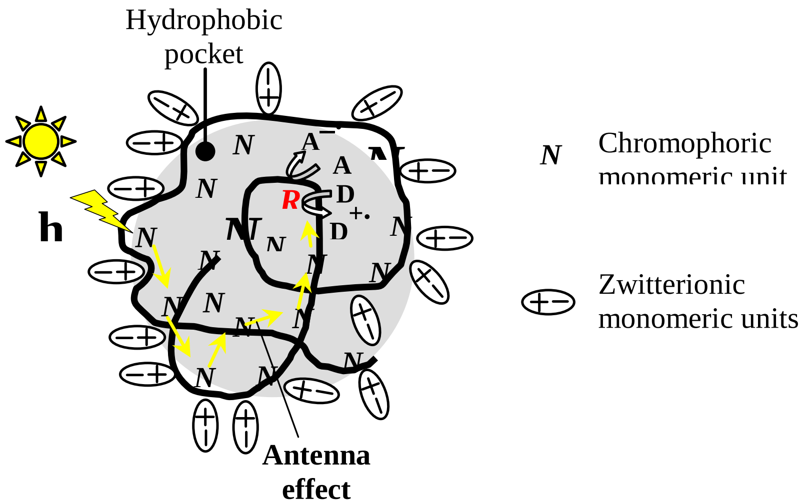

Figure 8.7 Conceptual illustration of light-harvesting and singlet oxygen formation in photozyme nano-micelle (R – antracene unit, acting as reaction center).

Achievements in 2007: First experiments performed with the photozymes synthesized in the labs of the University of Sofia. The objectives of these first tests were to find data on photozyme solution properties, optical characterization of the photozyme (absorption spectra etc.), behavior of photozyme solutions under irradiation, first test of photodegradation of model contaminants and arrive at conclusions for the synthesis of next generations of photozyme catalysts.

Publications: No publications are yet available

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

Participants: Royal College of Surgeons in Ireland (coordinator, Ireland); Univ. Ulster (UK); Council for Scientific and Industrial Research (South Africa); Swiss Federal Institute of Aquatic Science and Technology (CH); The Institute of Water and Sanitation Development (ZWE); CIEMAT-PSA (E); Univ. Leicester (UK); The International Commission for the Relief of Suffering & Starvation (KEN); Univ. Santiago de Compostela (E).

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Funding: EC-funded project, cost-shared (FP6, Specific measures in support of international co-operation 'INCO'): 1,900 k€

Duration: September 1, 2006 – August 30, 2009.

Background: Drinking water disinfection using *E. coli* as water quality indicator.

Objectives: The main project objective is to develop 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 manmade disasters. It will also develop appropriate technological innovations for SODIS enhancement that can be matched to varying socio-economic conditions. Such technological innovations would include dosimetric UV indicators for disinfection, photocatalytic inactivation and continuous water flow within solar collector arrays for small community distribution systems.

Figure 8.8 SODISWATER prototypes, PSA (E).

Achievements in 2007: During 2007 CIEMAT-PSA erected and installed two solar photoreactor prototypes at the Plataforma Solar de Almería (Figure 8.8). The experimental plan of work was focused in the determination of the role that different parameters play on the solar disinfection at pilot scale (total volume of treatment > 10 L). Water temperature, total volume, irradiated surface (Figure 8.9), flow rate and the use of CPC are now under study in real well water with *E. coli* K12 in flow SODIS reactors.

The lethal UVA dose for inactivating a certain bacteria suspension was found. Evaluation of disinfection as a function of the incoming solar UV energy (295-385 nm) received in the solar reactor leads us to conclude that total disinfection occurs only when a minimum UV dose is received in the system. It has been experimentally proven that this is not correlated with light intensity, since the lethal dose has been found to be the same for different irradiances. It was also found that when bacteria are exposed to the minimum dose, inactivation is gradual and does not occur immediately.

Publications: [8.22]-[8.26]

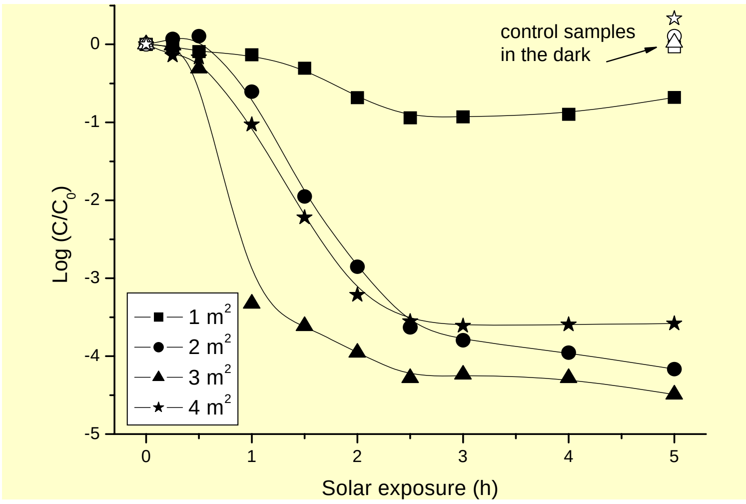

Figure 8.9 Inactivation of E. coli for different irradiated collector surfaces (total volume: 70L).

DETOX-H2S - Development of a new system for the elimination of airborne toxic and corrosive compounds generated in sewage treatment plants

Participants: CIEMAT-PSA (E), UNED (E), ICP-CSIC (E), ICV-CSIC (E), USACH (Chile), Univ. Wisconsin (USA)

Contact: Dr. Benigno Sánchez, CIEMAT-PSA, benigno.sanchez@ciemat.es

Funding: Madrid Regional Government (CAM): 700 k€

Duration: January 1, 2006 – December 31, 2009

Background: This project deals with the development of a new system for treatment of dangerous toxic substances, such as H_2S, mercaptans, amines, etc., which cause malodorous sewage plant emissions. Such foul-smelling chemicals strongly contribute to the difficult social acceptance of wastewater treatment facilities, and consequently their removal is a very relevant goal.

Objectives: a) Develop a photocatalytic treatment system activated by sunlight or UVA lamps suitable for operation under real processing conditions; b) Develop an adsorption treatment system that retains pollutants present in the gas streams under normal processing conditions; c) Based on the results of both systems, assemble a new combined photocatalytic-adsorption system which can exploit the synergy of both treatments. The achievement of these objectives should lead to a drastic reduction in the amount of chemicals currently required to control these emissions, creating a safer environment for plant workers and neighboring area.

Achievements in 2007: During 2007, a significant effort was devoted to the study of photocatalyst deactivation due to accumulation of sulfate formed as a result of H_2S photodegradation, and the possibility of subsequent regeneration with water. Data confirmed that photocatalytic films recovered their activity after sulfate removal, although a progressive decrease of photoactivity is observed following several regeneration cycles. In addition, the influence of relative air stream humidity on photocatalytic film performance was also studied. Results indicate that maximum conversion is achieved for 25-30% relative humidity (RH) depending on the particular material (Figure 8.10).

Publications: [8.27], [8.28]

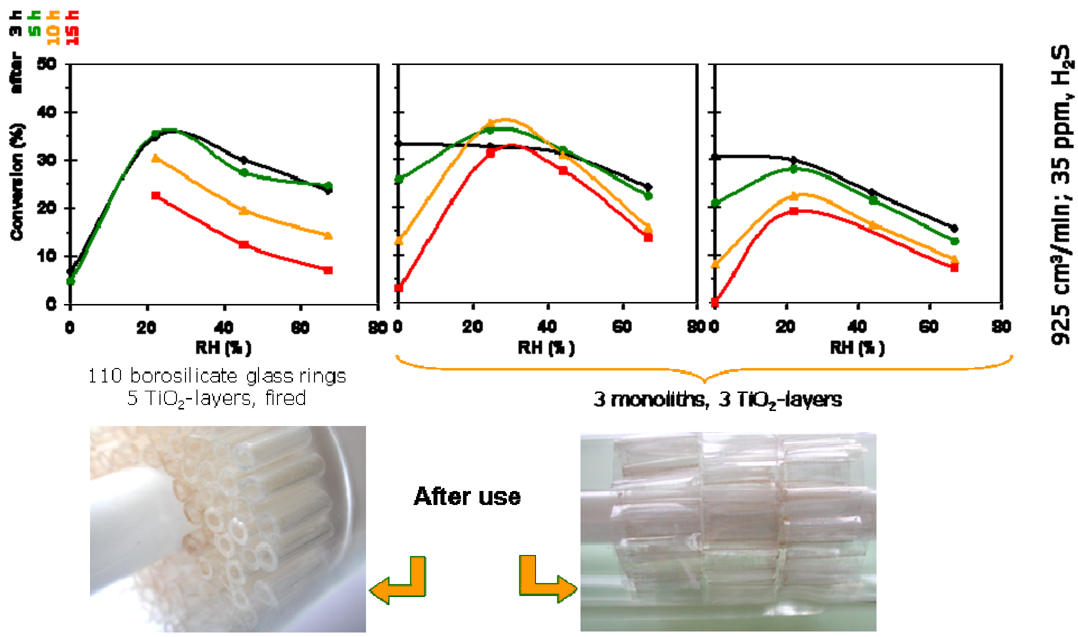

Figure 8.10 Conversion as a function of relative humidity, using glass rings and two polymers, PET and CA as TiO_2 catalyst supports

Development of alternative methods for the preparation of highly efficient photocatalytic materials

Participants: CIEMAT (PSA) and ICP-CSIC (E)

Contact: Dr. Benigno Sánchez, CIEMAT-PSA, benigno.sanchez@ciemat.es

Funding: Spanish Ministry of Science and Technology: 75 k€

Duration: January 1, 2005 – December 31, 2007

Background: The aim of this project is to satisfy the growing demand for versatile high-activity photocatalysts for the efficient elimination of air pollution. In particular, the removal of volatile organic compounds (VOCs), which in general are noxious and/or carcinogenic, is a very relevant target.

Objectives: A novel photocatalysts based on TiO_2 films (anatase), either pure or doped with Sn, Zr or noble metals, supported on various substrates (ceramic, metal, glass or organic polymers) will be developed. Incorporated extrusion, sol-gel impregnation techniques along with the innovative electrospray method will be used to deposit the photocatalyst layers. Then the photocatalytic activity and catalyst stability of the films will be measured to determine the influence of the different preparation variables on their performance

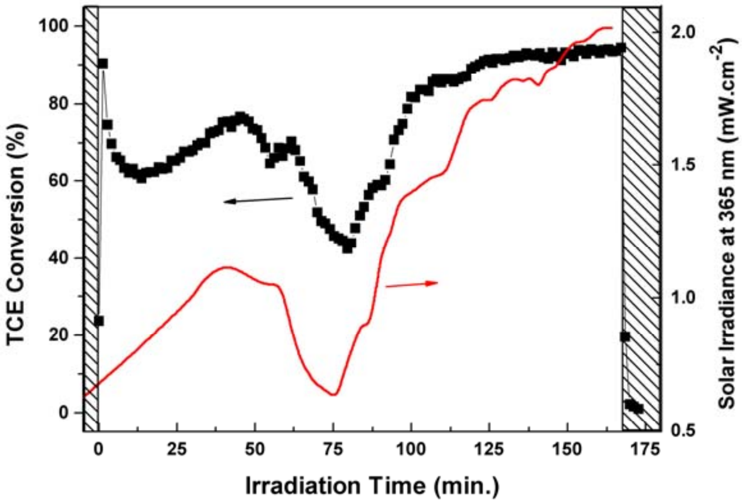

Figure 8.11 Variation in photocatalytic TCE conversion in air using a continuous flow solar reactor (Conditions: residence time of 2.3 s, TCE concentration of 590 ppmv). Changes in solar irradiance at 365 nm are also plotted as a function of irradiation time. Hatched areas show the results found when the gas stream is illuminated without photocatalyst.

Figure 8.12 Parabolic Trough Collector used for heating air and treatment experiments.

Achievements in 2007: CIEMAT tasks during 2007 have been mainly focused on the study of the activity of anatase photoactive films. The performance of the photoactive layers deposited on both opaque porous substrates based on ceramic (magnesium silicates), and nonporous transparent supports like borosilicate glass and organic polymers (PET, cellulose acetate), has been extensively tested under different operating conditions. In this respect, one of the most relevant achievements was the photocatalytic degradation of TCE under sunlight (Figure 8.11).

Publications: [8.29]

8.3 Outlook

Due to concern for water and energy issues, and the close relationship between both problems (water production requires large amounts of energy and power generation, especially from solar energy, also requires large amounts of water), a new Task has been added to jointly address technologically integrated solutions. Countries and regions with either water stress or water scarcity problems usually have high solar resources, and therefore, the integrated solution of water and energy problems, with sunlight as the primary energy source, is completely logical, and intense activity is foreseen in this Task during the coming years.

8.4 Meetings, Reports, Literature

Meetings:

The Task VI kickoff meeting was held on November 13, 2007, in Paris, in conjunction with the 73rd SolarPACES ExCo meeting.

Literature:

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[8.2] F.Trieb, H.Müller-Steinhagen, J.Kern, J.Scharfe, M.Kabariti, A.Al Taher, Technologies for Large Scale Seawater Desalination Using Concentrated Solar Radiation, Desalination (2008), in press

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[8.12] Agustín M. Delgado-Torres, Lourdes García-Rodríguez “Status of solar thermal-driven reverse osmosis desalination” Desalination 216, 242-251, (2007)

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[8.15] Agustín M. Delgado-Torres, Lourdes García-Rodríguez “Preliminary design of a solar thermal-powered seawater reverse osmosis system” Desalination 216, 292-305, (2007)

[8.16] Agustín M. Delgado-Torres, Lourdes García-Rodríguez “Double cascade organic Rankine cycle for solar-driven reverse osmosis desalination” Desalination 216, 306-313, (2007)

[8.17] Muñoz I., Peral J., Ayllón J. A., Malato S., Domènech X. (2006). Life cycle assessment of a coupled solar photocatalytic-biological process for wastewater treatment. Wat. Res., 40, 3533-3540.

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Part 9: Key Institutions and Persons

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