European Research on
Concentrated Solar Thermal Energy
Interested in European research?

RTD info is our quarterly magazine keeping you in touch with main developments (results, programmes, events, etc.). It is available in English, French and German. A free sample copy or free subscription can be obtained from:

Information and Communication Unit
Directorate-General for Research
European Commission
B-1049 Brussels - Belgium
Fax: (+32-2) 29-58220
E-Mail: research@cec.eu.int
Internet: http://europa.eu.int/comm/research/rtdinfo_en.html

EUROPEAN COMMISSION
Directorate-General for Research
Directorate J – Energy
Unit J.3 – New and Renewable Energy Sources
Contact:
Philippe SCHILD
European Commission
Office CDMA 5-141
B-1049 Brussels
E-mail: Philippe.Schild@cec.eu.int
Helpline: rtd-energy@cec.eu.int

For further information on Energy Research in the EU, please refer to the following Internet sites:
http://europa.eu.int/comm/research/energy/index_en.htm
http://www.cordis.lu/sustdev/energy
European Research on

Concentrated Solar Thermal Energy
Europe Direct is a service to help you find answers to your question about the European Union

Freephone number:
00 800 6 7 8 9 10 11

LEGAL NOTICE

Neither the European Commission nor any person acting on behalf of the Commission is responsible for the use which might be made of the following information.
The views expressed in this publication are the sole responsibility of the author and do not necessarily reflect the views of the European Commission.

A great deal of additional information on the European Union is available on the Internet. It can be accessed through the Europa server (http://europa.eu.int).

Cataloguing data can be found at the end of this publication.

Luxembourg: Office for Official Publications of the European Communities, 2004

ISBN 92-894-6353-8

© European Communities, 2004
Reproduction is authorised provided the source is acknowledged.

Printed in Belgium
PRINTED ON WHITE CHLORINE-FREE PAPER
Foreword

The White Paper “Energy for the Future: Renewable Sources of Energy – for a Community Strategy and Action Plan” set a minimum target for the European Union of 12% of energy to be supplied from renewable energy sources, including hydropower, by 2010. In the White Paper, a target of 1GWe was set for all renewable energy sources that had not yet achieved a significant market penetration. These sources include concentrated solar thermal, as no commercial power plants have been built anywhere in the world since the 1980s.

During the 1990s, the market conditions for concentrated solar thermal systems improved. Studies estimated that the installed capacity could be as much as 23GWe in the Mediterranean region alone by 2020. They also showed that the annual installation rate could reach 2GWe. Furthermore, EU-sponsored research activities have demonstrated the viability of the technology and helped to develop cheaper and more efficient components.

The development of concentrated solar thermal systems presents the research community with many challenges – in particular because these systems are more efficient and more economical at the large scale. The current economic and legal framework leads to installations being optimised at around 50MW, of generation capacity, representing an investment of around 200 million €. Fifty percent of this cost is in the solar field components, which therefore require a research focus on cost reduction. In addition, researchers are looking at the use of concentrated solar thermal power in novel applications such as hydrogen production. This widening of applications will open new markets and increase production volumes of solar components which should lead to a reduction in costs.

Collaboration at the European level offers the concentrated solar thermal research community a unique opportunity to coordinate know-how and resources, and to create synergies. Through these actions, the European Research Area for concentrated solar thermal systems will be shaped.

This publication presents an overview to help researchers, industry, and planners to work together to reach the ambitious targets set in the White Paper.

Pablo Fernández Ruiz

---

## Contents

- Foreword ................................................................. 3
- Introduction ............................................................. 7
- What is concentrated solar power? ............................. 8
- The different concentrated solar power systems .......... 9
- Concentrated solar power systems installed .............. 11
- Community support for concentrated solar power systems ......................................................... 13
- Potential of Concentrated Solar Power Systems ........... 15
- Research and technological development needs for concentrated solar thermal systems .......... 17
- Conclusion ............................................................... 19
- Research areas .......................................................... 21
Introduction

In 212 BC, Archimedes is said to have used mirrors for the first time to concentrate the power of the Sun’s rays. In 1615, Salomon De Caux invented a small “solar powered motor” which was the first recorded mechanical application of the Sun’s energy. His device consisted of glass lenses, a supporting frame and an airtight metal vessel containing water and air. It produced a small water jet when the air heated up and expanded during operation. In the 1860s, French mathematician, August Mouchet proposed an idea for solar powered steam engines. In the following two decades, he and his assistant, Abel Pifre, constructed the first solar powered engines and used them for a variety of applications. These engines became the predecessors of modern parabolic dish collectors for concentrated solar power applications.

These inventions laid the foundations for modern concentrated solar power technology. With the push towards sustainable power production and the increasing realisation for the need to reduce CO₂ emissions, renewable sources of energy are becoming an increasingly important element in the world energy balance. Concentrated solar power systems have the potential to replace conventional fossil fuels. They will also help mitigate the possible effects of climate change.

In concentrated solar power systems the Sun’s rays are focused through optical devices. These focused rays generate heat which can be used either to generate steam and electricity or to trigger chemical reactions. However, because electricity is one of the prime energy vectors in the world, electricity generation is likely to be the first application to become commercially viable. Further research and development activities will play a key role in bringing this technology to the market.

During the 1970s, methods of producing electricity via the solar thermal cycle were investigated. The efforts resulted in the further development of the technology and, in 1991, the first commercial power plant with a capacity of 354 MWₐ, based upon the concentrated solar power concept, was built in California, USA. This plant was erected over an area of 7 km² and feeds about 800 million kWh per year into the grid. However, most of the concentrated solar power plants in operation today are still at the prototype or demonstration phase and are dependent upon subsidies to make them competitive.

There is a need for financiers and planners to better understand the technical risk inherent in the first prototype installations, and to help developers to overcome financial barriers. There is also a need for researchers and developers to recognise the key issues required to enable systems to become efficient, reliable, safe and economical. Furthermore, the public has to be better informed about the potential and the benefits of this technology.

This brochure illustrates many of the current technical issues with examples of existing installations and energy projects supported under the European Community’s Framework Programmes for Research. In the first section, an overview of the technology is presented, including current achievements and future prospects. The second section describes the research areas covered by European Community funded projects since 1992, highlighting selected projects.
What is concentrated solar power?

Classical optical theory predicts that light rays travelling parallel to the axis of a spherical mirror will reflect off the mirror and pass through the focus of the mirror located a distance $R/2$ from the mirror, where $R$ is the radius of the mirror. The energy of all incident light rays combine at this point, effectively concentrating the light energy. This concentration produces heat, hence the name: concentrated solar power (CSP). So, in short, CSP systems use different mirror/reflector configurations to convert the sun’s energy into high-temperature heat. This heat can then be used directly or converted into electricity.

The main components of a CSP system are:

- **The solar collector field**
  This is the array of mirrors or reflectors that actually collect the solar radiation and focus it on to the solar receiver. The field is usually quoted in square metres which represents the surface area of the array, not the land use area.

- **The solar receiver**
  The solar receiver is the part of the system that transforms the solar radiation into heat. Sometimes this receiver is an integral part of the solar collector field. A heat transfer medium, usually water or oil, is used in the solar receiver to transport the heat to the energy conversion system.

- **The energy conversion system**
  The final component in the system converts the heat into usable forms of energy, in the form of electricity or heat.

Three different experimental configurations exist, as shown in figure 1. These are the parabolic trough, the parabolic dish and the central tower system. There is a fourth, the solar furnace, which is a hybrid of the central tower and the parabolic dish systems. These systems can be used for different applications as the concentrated heat they produce is at different temperatures, partly due to the size of the focal area.

In the parabolic trough, the focus is the focal axis of the trough collector. In the parabolic dish, the focal area is dependent upon the radius of the dish and is usually an area of a few hundred cm$^2$. In a central tower, the focal area is much larger, several m$^2$.

The average level of solar insolation is 1kW/m$^2$; the amount of solar energy available on the Earth’s surface. This can be concentrated several thousand times using CSP systems. The efficiency with which this radiation can be transformed into thermal energy is dependent upon a combination of optical efficiency and heat conversion efficiency. The optical efficiency of the system is defined by accuracy of the reflective shape of the solar collectors. Heat conversion efficiency is defined by the physical characteristics of the solar receiver to convert solar radiation to thermal energy. Optical efficiencies of up to 98% have been achieved along with heat conversion efficiencies of between 70 and 95%.

In CSP systems that produce electricity, the concentrated heat is used to produce steam, either directly or indirectly, which is then used to produce electricity. The efficiency of this system, solar to electric, is dependent upon the combination of radiation to thermal efficiency and of the steam cycle efficiency. Experimental installations have shown peak efficiencies of up to 29% for parabolic dish systems. This efficiency is dependent upon which system is used, with the most mature technology, the parabolic trough system being the least efficient.

CSP systems can also be used in chemical processes, for example hydrogen or metal production where the concentrated solar radiation is used directly as a heat source. Current laboratory experiments have shown chemical conversion rates close to 100%, i.e. all the raw material was successfully converted into finished product. However, due to current system design limitations, heat conversion efficiency is limited to 50%. Higher efficiencies are expected with improvements in the technology.
The different concentrated solar power systems

The main concentrated solar power systems are the parabolic trough system, the parabolic dish system and the central tower system.

The parabolic trough
This is the simplest form of CSP system, where the solar collector field is composed of rows of trough-shaped solar collector elements, usually mirrors, with an integral receiver tube, as shown in figure 2. They are parabolic in one dimension only and form a long parabolic shaped trough of up to 150m in length. The collectors are usually installed in rows and the total solar field is composed of several parallel rows. The collectors are connected to a single motor, controlled by a solar tracking control system, which ensures that the maximum amount of sunlight enters the concentrating system throughout the day. The solar receiver is a black-coated, vacuum glass tube containing the heat transfer fluid, either oil or water. The concentrated sunlight heats the heat transfer fluid to temperatures of up to 400°C, which can then be used to generate electricity using a turbine and an electrical generator.

The Direct Solar Steam project (DISS), a test facility at the Plataforma Solar de Almería (PSA) in Spain, has a solar field composed of 11 parabolic trough collectors with a north-south-oriented rotating axis and a total reflective surface of 2 750 m$^2$. The 11 collectors are each made up of 12m long by 5.7m wide reflective parabolic trough modules connected in series in one 550m long row.

The parabolic dish
A parabolic dish system, or solar dish, as they are sometimes known, is composed of a single structure supporting a parabolic dish covered in mirrors that reflect light on to a solar receiver located at the focal point of the dish, as shown in figure 3. On average, the dishes are between 8 and 10m in diameter, but in some cases they can be much larger, for example, the world’s largest is the ‘Big Dish’ in Australia which has an aperture of 400m$^2$. The Big Dish has 54 triangular mirror elements attached to the dish-frame and produces steam at 500°C, which feeds a steam engine driven generator connected to the Canberra grid.

Solar dishes are being developed mainly for electricity generation and, therefore, the solar receiver is combined with the energy conversion element which is usually a thermal engine, such as a Stirling engine or a Brayton cycle engine. Parabolic dish systems are the most efficient of all solar technologies, with peak efficiencies up to 29% efficient, compared to around 20% for other solar thermal technologies.

The different concentrated solar power systems

The central tower system

The central tower system is somewhat different in that the solar collector field is composed of several hundred individual, large sun tracking flat plane mirrors, called heliostats. These heliostats track the path of the sun throughout the day and focus the rays on to the solar receiver, see figure 4. The solar receiver can be an area of a few metres square which is located on the tower at a height of between 50 to 100 m according to the level of concentrated radiation to be collected. In these systems, a working fluid, either high-temperature synthetic oil or molten salt is pumped through the receiver where it is heated to 550°C. The heated fluid can then be used to generate steam to produce electricity.

The CESA-1 test facility is the only one of its kind in Europe and is located at the Plataforma Solar de Almería, Spain. It consists of a solar collector field of 300 heliostats distributed in 16 rows in a northern field, with a combined area of 11 880 m² and an 80m high concrete tower. Each heliostat is made up of 12 mechanically curved glass mirror facets. This installation is used to demonstrate the feasibility of central tower systems and their components, such as the heliostats, solar receivers, thermal storage and control systems. It does not produce electricity, but instead is used for other applications that require high temperatures, such as the production of methane and materials testing, for example, the testing of thermal shields of space vehicles simulating re-entry into the atmosphere.

Grid connection does not pose technical problems for CSP because in CSP plants the electricity generation utilises standard components from the power industries.

Fig 4: Picture of a heliostat, courtesy of Ciemat, PSA.
Concentrated solar power system installed

Applications
Concentrated solar power systems can be used for a range of applications depending upon the energy conversion utilised, electricity or heat. However, at present, most systems focus on electricity generation. The different types of CSP system, discussed above, are suitable for different applications, as shown in figure 5. The parabolic trough collector is the best solution for applications in the low temperature ranges such as detoxification, liquid waste recycling and heating water. All three systems are suitable for the mid-temperature range applications, and the central tower is the most suitable system because temperatures of more than 1 000°C can be easily sustained.

Current level of CSP installed capacity
Between 1984 and 1991, the world’s largest solar energy generating system (SEGS), totalling 354MWe, was built in the Mojave Desert in California, USA. The SEGS consist of nine solar thermal parabolic trough plants which can operate in hybrid mode as back-up using natural gas as fuel. No more than 25% of the electricity generated can originate from natural gas. In the best years the share of fossil fuels was less than 5%. It has been operating successfully on a purely commercial basis and has been running continuously since it was first commissioned, providing power for 250,000 homes. In addition, the annual output has increased by 35% as plant operations have improved over the past ten years and the operation and maintenance costs have decreased by 40% as a result of private research and development initiatives. A peak efficiency of 21% has also been reached, with annual efficiency running at between 14 and 18%. An annual capacity factor of 24% was proven. The annual capacity factor refers to the fraction of the year when the rated power is delivered in solar-only mode.

During the last ten years, several projects have begun around the world. However, the current economic

Fig 5: Applications for CSP systems
situation with low fossil fuel and electricity generation costs has made the operation of concentrated solar power plants non viable from a financial perspective. As a result, many projects have been forced to terminate due to lack of public financial support.

The infrastructure and the particular legal framework also affect the economics of an installation. The infrastructure influences which type and capacity of CSP system to install, and the legal framework determines the final design, the size and the financing, all of which affect the economics.

With the increasing concern for the environment over the last decade, in particular related to climate change, several initiatives from governments and public institutions have gone some way to improving the uptake of renewable energy sources as a viable alternative to traditional energy sources, such as coal and oil. The reliability of renewable energy technologies, including concentrated solar power, has increased whilst the costs have fallen. Following the results of a cost reduction study in 1999\(^5\), The World Bank established a financing programme, through the Global Environmental Facility (GEF), to fund up to 50 million $ of the incremental cost of a concentrated solar thermal installation within a conventional power plant in developing countries. As a result, concentrated solar thermal systems have benefited from increased interest from electrical generator companies, financing institutions and from governments around the world.

In 2003, there was a total of 2.7GWs demonstration projects in the pipeline, which represents more than 10 million m\(^2\) of solar collector field. Most of these projects aim to begin commercial operation before 2010. The total planned investment represents 4.5 billion €, including 200 million $ of GEF grants and 15 million € of grants for demonstration projects from the European Community’s Fifth Framework Programme for Research.

CSP costs
The economics of a CSP installation is strongly dependent upon its size. The size is defined in terms of the power output, but it is also directly related to land area. Nowadays, the minimum size of power plants is 1MWs for parabolic dish installations, 10MWs for central tower systems, and 50MWs for parabolic trough systems. It is likely that the cost of individual parabolic dishes will fall, which will open the market for smaller single units with an estimated cost of 5 000 €/kW. For central towers systems and parabolic troughs, present system costs are already below 3 000 €/kW, but the likely trend is towards larger installations of between 100MWs and 200MWs, which would lead to a reduction of this cost. Future plants of 1GWs are feasible if modular designs are utilised; this is comparable to the size of a nuclear power plant and would require 17km\(^2\) of desert land area.

However, developments in the technology will also ensure that the system costs decrease and cost reductions of up to 50% are expected as a result of a combination of several factors. The costs of a CSP system can, broadly speaking, be split into solar costs and non-solar costs. Reduction in relation to solar costs lies in mass production leading to economies of scale and in the development of innovative mirror systems, the solar collectors which currently constitute 30–40 % of the present plant investment costs, along with the development of novel optical systems. Non-solar costs will be reduced by the development of simpler and more efficient heat transport schemes, more efficient power cycles, direct steam generation, integration with conventional systems, and increases in steam temperature to improve the efficiency of the steam cycle for electricity generation.

A succession of three Commission funded projects, DISS, DISS-2 and the INDITEP project\(^6\), have been concentrating efforts on research into direct stream generation in the absorber pipes of parabolic trough collectors, as it is estimated that this development could lead to 26% reduction in the cost of the electricity produced.


\(^6\) Projects funded under the Community’s Fifth Framework Programme: DISS Project JOR3-CT95-0058, DISS-2 Project JOR3-CT98-0277 and INDITEP Project ENK5-CT-2001-00540.
One of the declared objectives of the European Union is to increase the share of renewable energy sources (RES) in the gross energy consumption to 12% and in electricity generation to 22.1% by 2010, from the levels of 5.3% and 13.8% respectively (in 1995). These targets are set out in the White Paper for a Community Strategy and Action Plan: Energy for the Future: Renewable Sources of Energy. This document also sets a target of 1GW for the installed capacity of concentrated solar thermal technologies, ocean energy systems and enhanced geothermal systems.

This Strategy and Action Plan is implemented through a variety of measures, including the Campaign for Take-Off, a detailed programme of demonstration and dissemination activities, and the Directive on the promotion of electricity produced from renewable energy sources (RES) in the internal electricity market. The status of implementation is being monitored by the Commission and levels are increasing. Results showed that in 2002, the share of RES was 5.1% for consumption and 13.4% for electricity generation.

There is now Community support for concentrated solar power technology and several Member States, including Spain, Italy and Germany, have launched initiatives to support the technology. The Royal Decree 436/2004, approved by the Spanish Council of Ministers on 13 March 2004, grants different options to the CSP generators, giving a range of premiums linked to the average reference tariff for the first 25 years of operation for a maximum unit power of 50MW. The Spanish Plan for the promotion of renewable energies also has a market objective of 200MW solar installed capacity by 2010. Italy has also approved a four-years development programme with a budget of 100M €, under the leadership of ENEA, the Italian National Agency for New Technologies, and in 2001 Germany launched a 10.5 M€ R&D programme on high-temperature solar thermal power generation technologies.

In the European Union, research activities were dominated during the 1980s by four countries: Germany, France, Italy and Spain. Today, only two large test facilities remain in operation: Odeillo (France) and PSA (Spain). In addition, there are several small solar furnace test facilities of 10 to 50kW capacity located in other Member States of the Union.

Odeillo in the French Pyrenees has the world’s most powerful solar furnace capable of focusing 1MW and reaching temperatures in the range 800°C to 2 500°C. This power is used to study the behaviour of processes and new advanced materials at high temperatures, for energy, space and environment applications. The European Test Centre for Solar Energy Applications (PSA), located near Almería, Spain, is undertaking research into parabolic trough collector technology, central receiver technology and solar chemistry, to develop new and improved ways to produce solar thermal electricity, and how to exploit the chemical and thermal possibilities of solar energy for detoxification of industrial effluents, the synthesis of fine chemical products and the desalination of water.

The research topics related to CSP technology covered by the Fourth and Fifth Framework Programmes, over the last ten years, represent 22 M€ of European Union Community support for concentrated solar power systems.

---

Fig 6: Framework programme support for CSP projects M€
contributions and have broadly focused on cost reduction and the development of receiver technology. The main research areas and projects funded are described in Section 2 of this document. An additional 15 M€ has also been used for demonstration projects under FP5.

The main results of these projects include:
- proof of the concept of Direct Steal Generation using parabolic trough collector systems leading to an estimated cost reduction of 25% in capital costs;
- a new parabolic trough collector structure with costs of less than 200 €/m²;
- a new parabolic dish system with unit cost of 5,000 €/kW, assuming a production of 250 units per year;
- proof of the concept of a solar gas reforming process;
- adaptation of gas turbine technology for use with CSP systems;
- the development of a new and better performing central tower receiver;
- development of the technology for the production of hydrogen and metal as energy carriers.

Following these successes, two demonstration projects are now in progress in Spain. One is the PS10 (Planta Solar 10) project and the other is named AndaSol.

The objective of the PS10 project is to design, construct and operate, on a commercial basis, a 10 MWe central tower system producing electricity in a grid-connected mode and based on volumetric air technology. The project is located near Seville, with 981 heliostats and a 90m high tower, and it is predicted that the plant will achieve an annual electricity production of 19 GWh net, with an installed cost of less than 2,800 €/kW, and a payback time of eight years. The start of operation is planned for early 2006. The project is receiving 5 M€ support from the Commission Fifth Framework Programme.

The AndaSol project, in Andalusia, Southern Spain, consists of two units of 50MWs solar plants using parabolic trough collectors with storage capacity. The partners anticipate that the electricity costs resulting from this installation will be 0.15 €/kWh, with a saving of 350,000 tonnes of CO₂ annually in Spain¹¹ and the creation of 116 permanent jobs in the region. The estimated project cost is 400 M€. The start of operation is planned for early 2006 and a second and third site have already been reserved for project replication. The Commission Fifth Framework Programme is supporting the completion of one of the units with 5 M€.

The parabolic trough collectors used in the AndaSol project are based upon a design developed in a previous Commission Framework Programme funded project, the EuroTrough project, described in Section 2. AndaSol will validate this new trough design and should show that an installed cost of less than 2,500 €/kW is feasible.

Potential of concentrated solar power systems

Contrary to its sister technology photovoltaics, concentrated solar thermal requires a direct line of light to the Sun to function at peak efficiency. Global solar irradiance consists of a combination of direct and diffuse radiation. Solar thermal power plants can only operate using the direct irradiance, whereas photovoltaic technology can use both direct and indirect radiation. Therefore, full exploitation of the CSP technology is limited to those geographical regions where the annual direct irradiation levels are high; the so-called Sun-belt area, where the annual horizontal irradiation levels are between 1800 kWh/m$^2$ and 2500 kWh/m$^2$.

Fig 7: Economically viable regions for CSP (shown in orange)

This area covers mainly desert zones and includes many developing countries. In theory, a fairly small area of the Sahara desert could be used to provide enough electricity to supply the whole of Europe. CSP systems could be utilised to harness this power, but more research is needed to assess the practical issues in order to be able to realise the full economic potential.

In 1996, the market potential for electricity generation systems using concentrated solar power technology was estimated, for the Mediterranean area alone, to be approximately 23GW$_e$ by 2025$^{12}$. About two-thirds of this economic potential is in the Northern Mediterranean countries$^{13}$. A further study for the World Bank in 1999$^{14}$ estimated the long-term annual installation rate to be 2GW$_e$. Electricity costs from concentrated solar power systems have reduced by over 50% in the last 15 years and are now estimated at 0.08 – 0.1 €/kWh for a plant operating in a high insolation region such as a desert$^{15}$. However, these studies only included systems which generated electricity and not those that generated process heat.

The European Commission Green Paper “Towards a European strategy for the security of energy supply”$^{16}$ estimated that 50% of the heat demand for European industrial processes is at a temperature of below 250°C. Concentrated solar thermal systems can provide heat at these temperatures, and can therefore contribute to providing secure energy supply for the Union.

The results of a joint IEA/EC workshop, in March 2002, highlighted that concentrated solar thermal systems are suitable for use in process applications ranging from the food/beverage sector to the textile and chemical sectors. Drying processes, evaporation, pasteurising, sterilising, cleaning and washing, chemical and biochemical reactors, and general heating of processes are all suitable applications for solar thermal systems. However, to realise this potential, the cost of the heat produced needs to fall to be comparable with that from conventional systems, currently 0.01 €/kWh.

The POSHIP project$^{17}$, a Community funded project designed to assess the potential of using concentrated solar power systems for generating low-temperature heat for industrial heat processes, showed that with

---

15 Tyner, Klob, Geyer and Romero; Concentrating Solar Power in 2001, Solar PACES.
17 The POSHIP project (funded by the Fifth Framework Programme for Energy, Environment and Sustainable Development), project NNE5-1999-0308.
the state-of-the-art technology in the Iberian peninsula, for applications below 60°C, heat costs in the range of 0.03 to 0.05 €/kWh are obtained, and at temperatures between 60 and 150°C, the cost is 0.05 to 0.1 €/kWh. The energy cost for German conditions is almost double, mainly due to the different irradiation levels further north in Europe.

The market potential for high-temperature applications is still unknown, but early research shows promising results. For example, the Spanish zinc smelters produced 385 million tonnes of zinc in 2001. Using concentrated solar power systems to provide the high temperature heat needed for the zinc smelting process could theoretically result in an environmentally clean and CO₂ neutral process.18

Meanwhile, CSP industries and proponents are pushing the introduction of CSP electricity power plants. Since 1995, several projects worldwide have been ongoing, but have been severely slowed down by legal and financial frameworks. In 2002, a group of CSP industries proposed a Global Market Initiative with a clear objective to install 5 000MWₑ by 2015. With this installed capacity, the cost of CSP energy will be reduced and confidence in the technology will grow. The group has already received support from financial and governmental bodies. The table below shows a list of projects currently in progress worldwide. For some of these, further development phases are already planned. The 10kWₑ EuroDish system, located in Seville (Spain), became the first Spanish and the first EU solar thermal generator to connect to the grid on 24 March 2004. With a power purchase contract under the new Spanish royal decree, a follow-up 1 MWₑ plant project is now being planned.

<table>
<thead>
<tr>
<th>Country</th>
<th>Location/Name</th>
<th>Type</th>
<th>Total Plant Power (MWe)</th>
<th>Solar Part (MWe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>India</td>
<td>Rajasthan</td>
<td>Hybrid</td>
<td>140</td>
<td>35</td>
</tr>
<tr>
<td>Egypt</td>
<td>Huraymat</td>
<td>Hybrid</td>
<td>127</td>
<td>31</td>
</tr>
<tr>
<td>Morocco</td>
<td></td>
<td>Hybrid</td>
<td>228</td>
<td>30 (est.)</td>
</tr>
<tr>
<td>Mexico</td>
<td></td>
<td>Hybrid</td>
<td>312</td>
<td>40</td>
</tr>
<tr>
<td>Spain</td>
<td>Seville / PS10</td>
<td>Solar</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Andalousia / Solar TRES</td>
<td>Solar</td>
<td>13</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Andalousia /Andasol</td>
<td>Solar</td>
<td>2 x 50</td>
<td>2 x 50</td>
</tr>
<tr>
<td></td>
<td>EuroSEGs</td>
<td>Solar</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Iran</td>
<td>Desert of Yazd</td>
<td>Hybrid</td>
<td>398</td>
<td>67</td>
</tr>
<tr>
<td>South Africa</td>
<td>Not known</td>
<td>Solar</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Israel</td>
<td>Not known</td>
<td>Solar</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Australia</td>
<td>Not known</td>
<td>Solar</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>USA</td>
<td>Arizona / Saguaro</td>
<td>Hybrid</td>
<td>150</td>
<td>43</td>
</tr>
<tr>
<td>Algeria</td>
<td>Not known</td>
<td>Solar</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>

18 Solar Carbothermic Production of Zn and Power Generation via a ZnO-Zn-cyclic Process, C. Wecker for SOLZINC-Consortium, (funded by the Fifth Framework Programme for energy, environment and sustainable development), Project ENK6-CT-2001-00512.
Concentrated solar power technologies still need further research to overcome non-technical and technical barriers. CSP projects require a long-term view in the same way as traditional energy producing plants, and therefore benefit from stable policies and continuity of legal and financial frameworks, ideally favourable for CSP. Cost reduction will result from technical progress.

The non-technical barriers are mainly financial and/or legal and could be overcome by adequate supporting tools for decision-making. Barriers include difficulties with access to the grid, authorisations to build plants, power purchase agreements, access to financing, environmental impact assessment approval, and permits to operate. Financial institutions look for performance guarantees and business plans to ascertain the revenue and the sustainability of projects, and at the moment they view CSP projects as high risk, resulting in the requirement for high returns on their investment, which could be as much as 25%. A major factor is the cost of the electricity produced, which is still high. Subsidies in the form of “electricity premiums” can significantly alter the economics of an installation. Policy-makers and lawmakers need to be informed in order to enable adequate support policies to be introduced, one of which could be premiums such as those set-up in Spain, as described early.

Technical barriers remain to be solved in order to bring CSP technologies into the energy markets. Nowadays, there are four important hurdles to overcome: resource assessment, performance improvement, component cost reduction, and operation and maintenance (O&M) cost reduction. Research in these areas will address the medium-to-longer-term needs of CSP technologies. In the short term, CSP project deployment will provide increased confidence in the technology as well as preliminary cost reduction through mass production.

Why is another resource assessment study needed? Solar radiation maps are well known and available, but they do not always provide policy-makers and developers with the real information needed to exploit the full economic potential of CSP. To install a CSP plant, a project developer needs to know the average annual available radiation at his location, and also the maximum expected deviations over a 20-year period. Furthermore, he also needs to know the land availability, suitability and access arrangements. Therefore, resource assessment studies need to link solar radiation levels with land use and topography. Urban areas, farm land and forest are not suitable locations. The need for extra access roads, and links to grid and water connections will also increase costs. Therefore, a resource map showing only the places where CSP could be deployed would offer both plant developers and policy-makers a good planning tool.

Improving the CSP performance is and will be a continuous ongoing research effort. First, improving the optical and the thermal efficiency of the solar components will mean that for the same power delivery, the solar field can be smaller and therefore the cost of the plant will be lower. Secondly, improving the efficiency of the electrical generation system will have the same effect. For example, operating a gas turbine at higher temperatures with CSP will increase efficiency of the turbine. Thirdly, improving operation performance and the operating hours will increase the total energy generated and therefore the revenue of a CSP plant. The elements to achieve a longer operation time are adequate storage systems, efficient start-up and shutdown procedures, and higher reliability of components. Finally, hybridisation brings together solar energy and other fuel, from fossil origin or from biomass. This concept can help to solve the intermittent nature of CSP output, therefore, increasing the performance of plants and could lead to further cost reductions.

Research and technological development needs for concentrated solar thermal systems
There are also opportunities to reduce the cost of the CSP components themselves. The solar elements of a CSP plant can represent up to 50% of the total cost due to the low number of such components manufactured today. Mass production will reduce these costs. This could result from the use of the optical components in other industries and diverse applications, e.g. industrial heat processes. In addition, costs may be reduced by new state-of-the-art designs, development of new materials and new components.

Operation and maintenance costs of the existing CSP plants have already been reduced by 25% over the last 15 years, but new technologies will be needed to reduce this further. Improved component design is needed to reduce mirror breakages that often occur under heavy wind loads or strong thermal stresses. Limiting breakages will also have the added advantage of providing longer operation hours. Limiting water requirements could also lead to cost reduction. For example, the use of cooling “dry-towers” will drastically reduce the water needs. Improved mirror performance requiring less cleaning also has advantages.

Clearly there are research and technological development needs that remain to be addressed and which will ultimately result in the improved performance, acceptability and uptake of this exciting technology.

Fig 9: CESA-1 Central tower test facility at Plataforma de Almeria, Spain.

Fig 10: 1MW solar furnace test facility at Odeillo, France.
Conclusion

Concentrated solar power energy has the potential to make a valuable contribution to the European energy portfolio. The concept is technically simple and sustainable and the potential lies both in the electricity generation sector and in the industrial processing sector. Furthermore, it can be exported easily to developing countries with high solar radiation, providing them with an opportunity to develop ‘clean’ power generation and industrial facilities. This potential has been recognised worldwide and European Union Member States have taken initiatives to promote both the energy generation and the industrial development of concentrated solar power technology.

European developers have taken up the challenge to demonstrate the financial viability of the technology and to widen the range of applications. The two commercial power plants currently being built in Spain, with a total installed capacity of 110MWe, should strengthen the position of the European CSP industry in the worldwide electricity generation market and encourage new installations, resulting in future cost reductions. Other research projects investigating various applications, including high-temperature solar chemistry for hydrogen production, are coming to fruition, which will open new markets. These developments will ensure the future viability of CSP.

However, there is still much to do and even though the technology has been largely demonstrated, the European Union faces the challenge of finally bringing it to the commercial market. This challenge can only be met by deepening collaborative work and by strengthening the European Research Area in this field. The achievement of this effort could be illustrated by 2010 with a European installed capacity of 500MW, and with the technical demonstration of an industrial-sized solar-enhanced fuel installation.

Fig 11: Eurotrough collector under test at the KJC powerplant in USA, courtesy of Flagsol GmbH.
RESEARCH AREAS

1994-2004
Abstract

The main challenges today for concentrated solar power plants are to improve operating performance and reduce costs, both in terms of capital investment and operation and maintenance (O&M), to be able to generate electricity at less than 0.08 €/kWh. Three consecutive projects have pursued this objective by developing and testing new and more efficient concepts for parabolic trough collectors using water as the heat transfer medium through Direct Steam Generation (DSG).

DSG in the solar trough collectors offers a substantial reduction in cost due to the reduced need for equipment and maintenance when compared to conventional technology, which typically uses synthetic oils as the heat transfer medium. Heat exchange is thought to improve the process. The first project, DISS, focused on the development, the construction and the commissioning of a 300kWth DSG test loop. The follow-up project, DISS-2, tested the three basic steam generation processes (once-through, re-circulation and injection). INDITEP, the third project, is now developing and testing new components in order to increase the operational temperature by 50°C to 500°C, to improve the performance of the steam turbine.

Challenges

In conventional solar electric generating system (SEGS) plants, parabolic trough collectors are used to concentrate the solar radiation, with synthetic oil as the heat transfer medium. These plants have already improved their efficiencies and lowered Operation and Maintenance (O&M) costs, resulting in a reduction of electricity generation cost to 0.10-0.15 €/kWh. Direct Steam Generation (DSG) offers a new and innovative means to achieve even further cost reduction.

The technical challenges were to prove the feasibility of stable two-phase flow operation mode using water, to gain information on O&M costs and procedures, to test the three basic steam operating modes (once-through, re-circulation and injection) at three different operating pressures, and to identify further technology improvements.

The approach was to test sequentially each step of the process. First, a single row of 11 solar collectors, capable of producing 300kWth, was built with water as the heat transfer fluid within a test loop to extract steam. The row was divided into water evaporation and superheated steam sections. In the first section, the water is evaporated through nine solar collectors. In the second section of three collectors, superheated steam, i.e. steam at temperature above 400°C, is produced. Secondly, the three different operation modes (once-through, re-circulation and injection), and pressures were then tested. In the once-through mode, water goes once through both sections. In the re-circulation mode, a given amount of water is taken after the first section and re-injected at the beginning of the loop. In the injection mode, a given amount of water is taken after the first section and re-injected at different points in the water evaporation part. Re-injecting hot water into a cold water part is thought to improve the process.

Thirdly, component improvements identified during manufacture and testing were evaluated. Finally, an economic assessment of the technology was performed which led to the development of a large-scale prototype plant.

The European Commission, through the Directorate-General for Research, has financed three research projects related to DSG, spanning the Fourth and Fifth Framework Programmes. The projects represent a continuous line of research and development. The first project, “Direct Solar Steam” (DISS), looked at the design of a real-size 300kWth test loop, the design of a control scheme for the three main operating modes (once-through, re-circulation and injection) and evaluated the potential of solar collectors for increased efficiency and reduced cost. In addition, an economic assessment of the technology was undertaken. The second project, “Direct Solar Steam – Phase 2” (DISS-2), investigated the three operation modes, developed and implemented components following the improvements identified in the first project, and defined promising plant concepts for a DSG commercial power plant into either combined cycle plants or SEGS-like plants. The third project, “INtegration of Direct solar steam Technology for Electricity Production” (INDITEP), continued the solar component improvements, developed new components able to operate at high temperature, increased the test loop by 200m to further study the re-circulation mode of operation and, lastly, designed a 5MW, solar-only plant.

All the projects maintained a balance between experimentation, theoretical development and economic evaluation. The project team consists of a partnership between utilities, component manufacturers, plant developers and researchers and has remained intact since the outset,
ensuring continuity of the work. CIEMAT (research) was the coordinator for DISS and DISS-2, the two first projects; Iberinco (utility – research branch) is now the coordinator of the follow-up INDITEP project. The change of co-ordinator for the final project is an indication of the successful development of the work, as it has moved from being research led to being industry led, with the focus now on application of the technology to a real situation and demonstration at a larger scale.

**Expected Impact**

DSG technology offers a means of producing high-quality steam from a renewable source: solar radiation. It is, therefore, free of greenhouse gas emissions. The power range varies from 500kWth to more than 200MWth. The technology is both simple and advanced. Its simplicity lies in the solar collector characteristics and materials. Its complexity lies in the control systems and operating strategies. Because of its power range, of its technical specificity, and of its cost, this technology is well adapted for industrial applications. The potential market for the technology is within the sun-belt area of both developed and developing countries, where there is a high annual average solar irradiation, above 1 600kWh/m².

The INDITEP project is focusing on the decentralised generation market, with the development of a small size module, in the range 5 to 10MWth. Such a small size module would be cheaper and easier to implement, offering an opportunity for a larger number of installations, which should reduce risk, lead to economies of scale, and ensure better visibility.

**Progress to date**

Construction and commissioning of the 300kWth solar loop, the world’s largest and first prototype of its kind, was completed in 1998. It is located at the Plataforma Solar de Almería in Spain. The preliminary economic assessment using this test loop technology, when extrapolated to an 80MWth generation plant, showed the possibility of reducing electricity generation costs by 26%. In 2001, super-steam generation at 450°C was successfully demonstrated under real solar conditions in the three operation modes. The tests showed that the re-circulation mode was the easiest to operate. The test-loop was operated for more than 3 600 hours over 37 months, averaging approximately 1 200 hours per year. A commercial installation is expected to average 2 500 hours per year. Operational experience has reduced start-up time from 1:45 hours to around 1 hour. Improvements have also been made on the sun-tracking controller, on the mirrors, on the solar receiver coatings and, in addition, a secondary stage concentrator was tested. The updated cost analysis has shown that the target electricity cost could be achieved with a reduction of 15% in capital investment costs and global efficiency increase of 15%. The same analysis also showed that an increase in the steam temperature to 550°C would increase the global efficiency by a further 4%.

The INDITEP project which started in July 2002 increased the test-loop length to 200m, enabling 2.3MWth to be generated. Tests started in Spring 2004 and the investigations to improve the solar collector components are progressing well. The preliminary design of a pre-commercial DSG plant is also under way.

### INFORMATION

**Project DISS**
Reference: JOR3-CT95-0058
Duration: 35 months
Total cost: 4.280.996 €
EC funding: 2.000.000 €
Status: Completed
Partners:
- CIEMAT (ES), Co-ordinator
- Deutsches Zentrum für Luft- und Raumfahrt (DE)
- Pilkington Solar International GmbH (DE)
- Iberdrola (ES)
- Union Electrica Fenosa (ES)
- Empresa Nacional de Electricidad (ES)
- Instalaciones Abengoa (ES)
- Siemens AG (DE)
- ZSW (DE)

**Project DISS-2**
Reference: JOR3-CT98-0277
Duration: 37 months
Total cost: 5.592.620 €
EC funding: 2.500.000 €
Status: Completed
Partners:
- CIEMAT (ES), Co-ordinator
- Deutsches Zentrum für Luft- und Raumfahrt (DE)
- Pilkington Solar International GmbH (DE)
- Iberdrola (ES)
- INITEC (ES)
- ENDESA (ES)
- Instalaciones Abengoa (ES)
- ZSW (DE)

**Project INDITEP**
Reference: ENK5-CT-2001-00540
Duration: 36 months
Total cost: 5.397.570 €
EC funding: 2.698.785 €
Status: In Progress
Partners:
- Iberdrola Ingenieria Consultoria (ES), Co-ordinator
- CIEMAT (ES)
- Deutsches Zentrum für Luft- und Raumfahrt (DE)
- Flabeg Solar International (DE)
- INITEC (ES)
- Instalaciones Abengoa (ES)
- ZSW (DE)
- GES (ES)

Contact point:
Fernando Rueda Jimenez
Tel: +34 913 83 31 80
Fax: +34 913 83 38 86
frj@iberdrolaingenieria.es
Abstract

Today’s commercial solar thermal power plants use parabolic trough collectors designed during the 1980s. These collectors are used together and make up the solar field of a power plant; this element alone represents almost 50% of the total investment cost needed. Therefore, in order to reduce the electricity generation cost to less than 0.08 €/kWh, the price of the parabolic trough collectors, and consequently the solar field, must be reduced. Two projects, EUROTROUGH and EUROTROUGH II, are European research projects designed to tackle this.

Their main target was to reduce the installation costs of a solar field to below 200 €/m$^2$ for an 80MW, solar thermal power plant. The research focused on several areas, including extending the collector length, improving wind induced optical losses, reducing critical stress of mirror facets and the demonstration of a thermal collector peak efficiency of 60% at normal incident design radiation of 850W/m$^2$. Increasing the collector length reduces the need for central collector tracking drives in the solar field. Reducing the stress on the mirror facets will induce less mirror breakage from wind load and therefore improve performance and reduce maintenance costs.

Solar Trough: Collector Development

Challenges

The challenges of the two European research projects, EUROTROUGH and EUROTROUGH II, were to re-think parabolic trough collector design originating from the 1980s, and to build a cheaper and more efficient modern version. Traditional solar collector assembly is composed of 16, six meter long parabolic trough solar collectors, making a 100m length solar collector assembly, which is controlled by a single drive pylon in the centre. In a solar field, the solar collector assembly is considered to be a single unit, which moves in unison following the sun. The approach taken in the projects was to address the challenges in two stages. The EUROTROUGH project focused on the design of the individual solar collector element to improve optical performance under wind loads and reduce costs during manufacture and assembly. In EUROTROUGH II, the aims were to continue the improvement of the basic design and to extend the length of a parabolic trough solar collector assembly by 50% to 150m.

The European Commission, through the Directorate-General for Research, financed the two research projects, spanning the Fourth and Fifth Framework Programmes, FP4 and FP5. In the first project, EUROTROUGH, the basic design, called LS3, as used in existing concentrated solar thermal plants in the USA, was investigated in a wind tunnel and its behaviour simulated using advanced computer models. Then, a new concept was designed, built and tested. In the second project, EUROTROUGH II, the prototype was extended and then tested.

In order to qualify the performance of the new design, comparisons needed to be made with the LS3 parabolic trough collector design. The consortium chose to use an existing installation at the Plataforma Solar de Alméria and installed a collector assembly consisting of the new design parabolic trough elements in parallel to the existing LS3 parabolic trough elements. In this way, tests under the same conditions could be done on both designs at the same time, and comparisons of performance made.

In both projects the consortium included partners with strong expertise in concentrated solar power technologies, market deployment and in design and manufacturing processes. This combination guaranteed that the new design would have better performance and be easily manufactured in large quantities. From the start, the projects were designed in such a way as to ensure that new design could be easily exploited. A parabolic trough receiver manufacturer joined the consortium for the second phase project.

Approach and Results

The research activities focused on the theoretical and experimental analysis of the performance of a 150m parabolic trough collector assembly using new design parabolic trough elements, under various insolation and wind load conditions. Comparisons were made with the conventional design solar trough collector assembly. The projects covered many elements including the development of design concepts, collectors and entire fields. The detailed design, engineering, procurement and manufacturing of materials and components for the test loop extension were also considered and new measurement methodology and procedures were developed. New optical characterisation techniques of flux density measurement and photogrammetry for efficiency analysis were also developed and tested. A complete new data acquisition system was installed and techno-economic case studies for implementation in the sunbelt countries were
Other areas investigated include a finite element method analysis to investigate the mechanical behaviour of the collector under dead and wind loads and the use of ray-tracing software to predict optical behaviour of the structural design and the optical performance of the new design.

During the tests, the new solar collector design, known as EUROTROUGH, showed stronger resistance to wind loads and improved operational performances than the traditional design, and a peak optical efficiency of 74%. At 350°K above ambient, the global efficiency, radiation to thermal, was measured at 66%. The economic performance of the new design was also evaluated using simulations for a 50MW$_{th}$ plant. The evaluation showed that substantial cost reduction can be achieved through the reduction of the number of components such as hydraulic drive systems. Furthermore, the analysis highlighted scope for further cost reduction in areas such as the supporting structure and assembly procedure. A reduction of metal parts by 15% and manpower needs by up to 22% were also shown to be possible.

As part of the research projects, two case studies using the EUROTROUGH concept were analysed and compared, one at Marquesado de Zenete, Spain and one in Mexico. The Spanish case study uses a Solar Steam Cycle configuration, which is a solar-only plant in which superheated steam is produced at 370°C and at 100bar using synthetic oil as the heat transfer medium in the parabolic trough collectors. The Mexican case study uses an Integrated Solar Combined Cycle configuration, which is a dual fuel plant combining solar and fossil fuel. An integrated solar combined cycle plant combines mature steam turbine technology with mature solar technology, in which the steam produced from the solar field is injected into the “classic” steam cycle, leading to reduced CO$_2$ emissions as less fossil fuel is needed. In this case a Brayton cycle was chosen capable of achieving thermal efficiency above 55%.

The EUROTROUGH I and EUROTROUGH II projects were both successful and fulfilled all their objectives. Half a parabolic solar collector assembly, 75m section, was completed using the EUROTROUGH design, and was tested under real sunshine conditions for one year. This collector showed that 1 300kWh thermal per year at a site with 2 300 kWh/m$^2$ annual direct radiation giving a performance of 60% annual thermal collection efficiency can be achieved. These performance and design improvements yielded a 15% cost reduction when compared to existing technology.

As a result of these projects, the industrial partners are now EU leaders in low-cost parabolic trough technology and are beginning to tender for new solar thermal power plants using the EUROTROUGH design. Two consortium partners, Solucar and Flabeg Solar, are developing demonstration projects for up to 50MW$_{th}$ power plants in Spain. One, named AndaSol-1, is located at the site selected for the Spanish case study. This demonstration project is receiving EU funding under a fifth R&D Framework Programme contract. The industrial partners have also pursued development with financial help from a German research programme, to install a full-size loop at the solar power plant at Kramer Junction in the USA, in order for the design quality under commercial operational conditions.

As part of the research projects, two case studies using the EUROTROUGH concept were analysed and compared, one at Marquesado de Zenete, Spain and one in Mexico. The Spanish case study uses a Solar Steam Cycle configuration, which is a solar-only plant in which superheated steam is produced at 370°C and at 100bar using synthetic oil as the heat transfer medium in the parabolic trough collectors. The Mexican case study uses an Integrated Solar Combined Cycle configuration, which is a dual fuel plant combining solar and fossil fuel. An integrated solar combined cycle plant combines mature steam turbine technology with mature solar technology, in which the steam produced from the solar field is injected into the “classic” steam cycle, leading to reduced CO$_2$ emissions as less fossil fuel is needed. In this case a Brayton cycle was chosen capable of achieving thermal efficiency above 55%.

The EUROTROUGH I and EUROTROUGH II projects were both successful and fulfilled all their objectives. Half a parabolic solar collector assembly, 75m section, was completed using the EUROTROUGH design, and was tested under real sunshine conditions for one year. This collector showed that 1 300kWh thermal per year at a site with 2 300 kWh/m$^2$ annual direct radiation giving a performance of 60% annual thermal collection efficiency can be achieved. These performance and design improvements yielded a 15% cost reduction when compared to existing technology.

As a result of these projects, the industrial partners are now EU leaders in low-cost parabolic trough technology and are beginning to tender for new solar thermal power plants using the EUROTROUGH design. Two consortium partners, Solucar and Flabeg Solar, are developing demonstration projects for up to 50MW$_{th}$ power plants in Spain. One, named AndaSol-1, is located at the site selected for the Spanish case study. This demonstration project is receiving EU funding under a fifth R&D Framework Programme contract. The industrial partners have also pursued development with financial help from a German research programme, to install a full-size loop at the solar power plant at Kramer Junction in the USA, in order for the design quality under commercial operational conditions.
Objectives

Solar thermal power plants in Mediterranean countries present an excellent option to contribute towards reducing CO₂ emissions. For large plants, in excess of 50MWₑ, two technologies currently compete: parabolic trough collector technology and the central tower system (see part 1). However, at present there is not yet a commercial plant in operation based on the central tower technology. The main obstacles to this are the costs of the solar field and of the solar receiver, the high operating temperatures and the associated high technical risks. Nevertheless, Europe’s first commercial central tower power plant is now being planned in southern Spain.

Looking forward to future generations of power plants, further cost reduction and improved reliability and performance are necessary. Therefore, a research project, SOLAIR, recently completed, developed and demonstrated a new volumetric air receiver concept, based on ceramic volumetric absorber modules. The project objective was also to design a modular system that would allow mass production potential and would facilitate up scaling to larger systems.

Challenges

The main aim of the project was to design a cheaper and modular solar receiver based on ceramic volumetric absorber modules. Ceramics have not been used in this technology to date. The objectives were to create a receiver made of ceramic modules that uses air as the heat transfer medium which could operate at solar flux up to 1.5MW/m² with an outlet air temperature of 750°C and with a cost of less than 35 000/m². Furthermore, the receiver design should include a large enough safety margin to allow safe operation in all weather conditions.

Using air as the heat transfer medium leads to several advantages because air is an easy medium to work with; it is abundant, free and environmentally benign. A high operating solar flux and outlet temperature lead to smaller solar field requirements and associated cost reduction. However, this also means that the solar facing surface of the receiver needs to be protected from hot spots where temperatures above 1000°C could be reached and cause damage. The receiver design needs to be modular, simple and easy to manufacture which will lead to a reduction in costs.

To tackle the technical risks inherent in such a project, the consortium planned the work to run in two consecutive phases. In the first phase, the main design parameters and choice of materials were to be solved and tested. In the second phase, the modular aspect of the new receiver was developed and tested.

In the first phase, ceramic materials were chosen as the receiver material, in preference to a metallic mesh because ceramics have better resistance to high temperatures and to weathering. From the start, the intention was to retain the modular aspect of the receiver. Therefore, it was designed as an array of ceramic absorber modules. The project set out to optimise the design, manufacture, treatment and assembly according to specified cost and performance requirements, and began with small-scale laboratory pre-tests to qualify the absorber module.

The supporting steel structure of the absorber modules, the warm air return system and the passive control elements were all developed with a view to homogenising the receiver outlet air temperature. All the components were to be qualified, assembled and tested as part of a new 200 kWₑ receiver to be tested at the Small Solar Power System (SSPS) site of the Plataforma Solar de Almería (PSA). The SSPS site consists of 93 heliostats with a total reflective surface of 3 655m². In addition, material investigations on absorber material degradation were to be performed with the exposed elements, in order to estimate lifetime expectations.

From the results obtained during the first phase of the project, the second phase was designed to develop and test a larger receiver to provide the necessary intermediate step in the scale-up to a large scale application, to reduce technical and commercial risks. Given that current concentrated solar thermal central tower plants are at least 10MWₑ, i.e. about 30 MWₑ, a 3 MWₑ receiver was chosen as a good intermediate step. The receiver was to be designed to allow scale-up through its modularity. It was to be tested at a second site of the Plataforma Solar de Almería, the CESA tower which has 300 heliostats representing a total reflecting area of 11 880m².

In parallel, a detailed optimisation analysis on solar power plant cycles was to be performed to fully exploit the expected benefits of this advanced receiver system.
The project combines the expertise from concentrated solar thermal research teams and industry with experts in material and industrial development of ceramic silicon carbide. The two-phase approach gives the project a strong base on which to develop and the flexibility for the partners to reach the objectives set at the beginning of the project.

Progress to date

Phase 1 of the project has been successfully completed. Suitable absorber ceramic materials have been selected based on the results from small-scale experiments and subsequent material investigation. Also, the detailed design and manufacture of the 200 kWth receiver has been completed. The receiver components were assembled, commissioned and tested at the PSA test site. The receiver was operated for a total of 182 hours under solar conditions. The resulting analysis demonstrated that outlet air temperatures above 750°C and an air return ratio of almost 50% was achieved. Thermal efficiency of 74% was also obtained.

The receiver is composed of 36 individual square-shaped absorber modules, butted together to form a larger unit, supported by a metal structure. The surface of the individual absorber modules is composed of the ceramic material, SiSiC, which can withstand high temperatures. The shape of the modules was changed from hexagonal to square to simplify installation and design.

Phase 2 of the project is now completed, with the 3MWth receiver designed, manufactured, delivered and installed by July 2003. This receiver unit is based upon the 200kWth receiver concept, from phase 1. The shape of the receiver was chosen bearing in mind that it was intended to be an intermediate step in the development of a larger 30MWth system. The 3MWth unit had a total surface area of 5.7m², on a metallic supporting structure. Preliminary results from the solar testing confirmed the positive results obtained during phase 1.

The receiver was operated for a total of 150 hours under solar conditions. The resulting analysis demonstrated again that outlet air temperatures above 750°C and an air return ratio of almost 50% was achieved. Thermal efficiency of 74% was also obtained.

The final outcomes of this project are the detailed design of a modular second-generation volumetric air receiver, and the demonstration of a 3 MWth prototype receiver system. In addition, an optimised cycle design is available, which is based upon the improved capabilities of the receiver with respect to high flux levels, large air return ratio and increased air outlet temperature. An overall reduction of solar electricity generating costs of about 10% is projected, when compared to current volumetric air receiver technology. As a result of the data obtained, the consortium’s industrial partners have gained confidence in the system and are now considering up scaling the solar receiver design to build a full solar power plant.
Abstract

The substantial investment needed for concentrated solar thermal technologies and the limited number of sun hours available during the year mean that electricity generation costs are high. One way to increase the electricity generation hours is to combine solar thermal technology with energy storage capabilities, but this has cost implications. However, there is another option which is to combine the use of solar energy with fossil fuel in a solar-hybrid plant. The SOLGATE project investigated a solar-hybrid plant to demonstrate the applicability and feasibility of the concept.

The innovative idea was to use a solar tower system to heat air at high temperatures that could be fed into a modified gas turbine. The modified turbine allows three modes of operation, with fossil fuel only, a mix of fossil fuel and solar, or solar only. In this way, continuous operation can be achieved maximising the use of solar energy when it is available.

The objective of the project was to provide an electricity generation cost of 0.069 €/kWh using a system with direct solar heating of pressurised air for the gas turbine, using 50% solar share. This represents a significant cost reduction for solar electric power generation, and had an anticipated investment cost of 1410 €/kW. The project was successful and proved the technological feasibility, performance and cost reduction potential of such power plants.

Challenges and Approach

The objective of the project was the development of a solar-hybrid power system with direct solar heating of pressurised air for use in a modified gas turbine, to achieve cost reductions for solar electric power generation. The modified turbine was to be tested in three modes of operation, with fossil fuel only, a mix of fossil fuel and solar, or solar only.

The main solar components for a solar tower system are standard equipment, and although their costs could be reduced further, the project consortium decided to focus on the development of the specialised components of a solar-hybrid power plant, the solar receivers and the modified gas turbine.

The objective of the project was to develop solar receivers capable of producing hot air at 1 000°C. A three-stage approach was chosen in which three different solar receivers could be used to increase the air temperature from 250°C, the outlet temperature of the gas turbine, to 1 000°C. These receivers were designated as low, medium, and high temperature receiver modules. While solar receiver designs and improvements were based on the pre-existing concepts developed by one partner, the aims were to lower costs, develop more reliable components and to improve performance. The existing low temperature tubular receiver module, corresponding to the first stage from 250°C to 500°C, was to be redesigned, with the emphasis on reducing the pressure drop and manufacturing costs. The existing medium temperature receiver module, from 500°C to 750°C, was not to be modified. A new high-temperature receiver module, from 750°C to 1 000°C, was then to be developed. Only three solar receivers, one for each stage, were to be built and tested with the gas turbine, due to limitations on the test area available.

The project aimed to modify both the combustion chamber of the gas turbine and the operating control system, to allow dual use of solar heat and fossil fuel. The gas turbine would receive air from the outlet of the high-temperature receiver module. This hot air would enter the modified gas turbine combustor that was not be optimised for efficiency. Considering that the normal operating inlet temperature of the chosen type of gas turbine is 800°C, the solar heated air to the gas turbine would need to be cooled from 1 000°C. A by-pass system would need to be implemented to keep the air temperature at the correct level.

Having a high-temperature solar receiver module able to produce air at 1 000°C allows the possibility of future developments and applications. The development of a gas turbine able to operate at higher temperature would allow the use of this solar technology without changes. All these new components were to be integrated into a complete solar-hybrid power system and installed in the 7MWth solar tower facility at Plataforma Solar de Almería in Spain. An eight month testing programme was designed to test all the relevant operating conditions and to demonstrate the performance of the components and the system as a whole, along with durability and maintenance requirements. Grid connection issues were also to be investigated including the development of software for simulating component and system performance.

Also as part of the project, the conceptual layout of prototype systems, based on three industrial gas turbines ranging from 1.4 to 17 MWth, using combined cycle and recuperated gas turbine configurations were to be assessed. The influence of modifications to the gas turbines was to be assessed in relation to cost and performance. Cost figures for the receiver system
and the components for integration were to be determined, the performance of the three systems analysed and the electricity cost evaluated. An assessment of the European and worldwide market potential was also included in the project.

**Results**

The project has achieved its objective to prove that a gas turbine can be modified to allow dual operation and that temperatures of 1 000°C can be generated in a pressurised solar receiver module.

A helicopter engine was modified to enable external solar heating with a design power output of 250kWe using natural gas as fuel. After modification, extensive commissioning tests were carried out with fossil fuel to verify the adaptation of the gas turbine and entire power control unit system. These commissioning tests were successfully completed, including a simulation of the solar operations.

A low-cost receiver module for temperatures up to 600°C, consisting of multiple bent tubes, was designed and manufactured. A high-temperature receiver module for 1 000°C was also designed and manufactured. High temperatures were achieved using ceramic absorbers in combination with active cooling measures on the receiver window. Three different types of solar receivers, a low air outlet temperature, a medium air outlet temperature and a high air outlet temperature, were built. They were integrated with the gas turbine on a portable platform containing the control cubicles and the whole installation was tested.

The test period was divided into two phases. In the first phase the tests were done with one low-temperature and two medium-temperature receivers. In the second phase, the high temperature replaced one medium-temperature receiver, resulting in one low-, one medium- and one high-temperature receiver available for testing. Solar testing has proven the solar components and system performance. The hybrid system performed as specified, efficiently and easily. The gas turbine was operated for 73h, of which 51h were with solar energy input due to the need to share the test facility with other projects. The estimated solar fraction of the generated electricity was 2.5MWh. Full evaluation will be made available in the final published report of the project.

The simulation models, design tools and predictive tools for control strategy were developed and assessed. Preliminary analysis of the measurements showed good correlation with simulation models. Three solar-hybrid gas turbine systems, with power levels of 1.4, 4.2 and 16MWe, were investigated in terms of performance and economic assessment. This analysis showed that for a 16MWe installation operating at 800°C the specific investment cost would be 1 440 €/kW, with an electricity generation cost of 0.057 €/kWh at 16% annual solar share. With an operating temperature of 1 000°C, a solar share above 50% is achievable, but then the electricity generation cost would be 0.086 €/kWh.

The consortium is now looking at opportunities to further reduce the system costs and to demonstrate the technology at a higher power level.
Abstract

Dish/Stirling systems, as described in the first section, are small units usually in the range 10 to 25kW. Dish/Stirling systems can be designed for either grid connection or for remote applications where they can benefit remote communities. However, cost and proof of long-term reliability are currently delaying uptake of this technology.

The project EuroDish, funded under FP4, had the objective of addressing the cost barrier to make the systems competitive for decentralised generation applications. The objective aimed to develop new innovative components, improve manufacturing/erection procedures and associated tools to reduce system costs to less than 5 000 €/kWe for a production level of 100 to 500 units per year.

Dish/Stirling: System Development

Challenges and Approach

The objective of the project is to make dish/Stirling systems competitive for small decentralised grid applications, just like diesel generators or PV applications in remote communities. Present dish/Stirling designs can be as much as 11 000 €/kWe for single prototype installations. The project aims to reduce the cost to 5 000 €/kWe, for a production level of 100 to 500 units per year.

The existing European dish/Stirling concept needs to be reassessed to reduce cost. Present prototypes are being built using of-the-shelf components, which are expensive and not well adjusted to the use in dish/Stirling applications. Four areas of dish/Stirling systems should be investigated, the optical dish design, the supporting structure, the Stirling engine and the control system. The project looked at optimising the dish/Stirling design for cost and performance to deliver a 10kW system. New adapted tools for small series production would also be developed to reduce the manufacturing costs for the Stirling engine, and a new installation procedure would be tested. Finally, a new erection procedure was developed which was simpler to install and needed less manpower.

Design of the turn table, the surface on which the dish rotates to follow the Sun, and its foundations were also improved and simplified. The drive system was also re-designed both to reduce cost and to enhance tracking accuracy.

The improvements made to the Stirling unit were in the cooling system, where the cooling cavity was replaced by a water-cooled version, and in the unit design, which was optimised. The solar receiver manufacturing process was also rationalised to reduce cost and improve quality.

The control system was equipped with an Internet server enabling remote monitoring of the dish/Stirling units. Performance was continuously monitored by all partners, and data and failure logs were available. This new feature brings other benefits in allowing performance to be supervised and problems to be recognised and therefore rectified at an early stage. The maintenance staff can then be fully prepared for corrective actions and repairs.

Results

A new innovative dish/Stirling system has been made available at a lower cost, which should open the market for medium-scale production of around 500 units per year. Two systems were erected during the project at the same location as the old standard design to allow performance comparisons to be made.

A detailed analysis of the manufacturing and erection processes and the operation and maintenance procedures, using simulation tools, highlighted a number of measures that could allow cost reduction.

The optical concentrator shell was modified, in terms of materials and supporting frame design. The well-proven metal membrane concept applied in former projects has the disadvantage of high erection cost in a single system installation. To overcome this, a new concentrator concept was adopted using a shell built up of 12 reinforced glass-fibre resin sandwich segments on a space frame ring truss. Special tooling required for manufacture of the segments was developed and built and the segments were fabricated and tested. In addition, a new erection procedure was developed which was simpler to install and needed less manpower.

Design of the turn table, the surface on which the dish rotates to follow the Sun, and its foundations were also improved and simplified. The drive system was also re-designed both to reduce cost and to enhance tracking accuracy.

The improvements made to the Stirling unit were in the cooling system, where the cooling cavity was replaced by a water-cooled version, and in the unit design, which was optimised. The solar receiver manufacturing process was also rationalised to reduce cost and improve quality.

The control system was equipped with an Internet server enabling remote monitoring of the dish/Stirling units. Performance was continuously monitored by all partners, and data and failure logs were available. This new feature brings other benefits in allowing performance to be supervised and problems to be recognised and therefore rectified at an early stage. The maintenance staff can then be fully prepared for corrective actions and repairs.
The two dish systems were operated continuously. The newly developed components proved to work easily. In the first system the performances remained below the desired values, whereas in the second one they almost reached the design power output. The cumulated operation time was 300h within the project duration and peak power of 10kWe was achieved.

Based on the present state of system development and construction, the cost for the dish/Stirling system has been evaluated to be near the target of 5 000 €/kWe, for a production level of 500 units/year. The analysis also highlighted potential areas for further cost reduction related to several components, thus improving the chances of achieving a cost level that would permit competitive entry into the market.

In the long term, the consortium is considering the options, which would allow the system designed in the project to be fully deployed in the energy market. As part of their exploitation vision, they foresee that local companies could be used to manufacture parts, install components and provide maintenance and repair functions. The market envisaged for these systems is to provide decentralised power production, especially in the Mediterranean countries. A recent study\(^1\) identified the market potential as 550MW, in this region, where the electrification rate for communities is low. Electrical energy is required to improve their standard of living, to reduce the consumption of imported fossil fuels and to boost craft and local industry. Nowadays, small diesel engines are most commonly used, which could be replaced by dish/Stirling systems in many cases. When energy is needed beyond the sunshine hours, hybrid dish/Stirling systems could be used.

\(^1\) Solar Thermal Power Plants for the Mediterranean Area; DLR 1992
Abstract

The high investment cost of concentrated solar thermal technologies and the limited number of sun hours available during the year mean high electricity generation costs. To increase electricity generation hours, one option is energy storage, implying cost increase for the overall system. The concept investigated here in this project looks at another option, based on a combination of solar energy and fossil fuel in a solar-hybrid plant. A dish/Stirling solar-hybrid plant could offer the advantages of continuous operation and of use in remote, non-grid connected applications, beneficial to small remote communities. Furthermore, the non-solar fuel could be based on biogas, resulting in a sustainable energy system. The key component is the solar receiver which has to be improved with respect to lifetime and economy, and has to be “hybridised”. Therefore, the following goals were pursued: the development of the heat pipe receivers, cost reduction using a new manufacturing method of the heat pipes, and demonstration of performance. One hybrid solar receiver has been built and tested for one year and is based at the Solar European Test Centre, Plataforma Solar de Almériá (PSA), Spain.

Challenges and Approach

A Stirling engine uses external heat sources to expand and to contract a fluid. In the dish/Stirling system investigated in this project, the fluid is helium, the cold source the ambient air, and the hot source the solar heat. In a Stirling engine the solar receiver is a black pipe structure, such as a radiator, that collects the heat from the concentrated radiation. Therefore, in order to heat the solar receiver from a non-solar source the solar receiver needs to be modified.

In the project, which is the first attempt to develop a hybrid solar-gas concept for dish/Stirling, a hybrid heat pipe receiver for dish/Stirling systems would be developed, allowing reliable power generation independent of solar radiation. This heat pipe would transfer any power combination from gas and solar input up to 45 kWth without temperature drop. A new low-cost method producing heat pipe capillary structures would be developed in order to reduce one of the main costs, the manufacture of hybrid heat pipe receivers.

An automatic control system would also be developed and implemented. Then the intention was for a hybrid heat pipe receiver to be installed in an existing dish/Stirling system at Plataforma Solar de Almériá, Spain and tested in all operation modes, solar-only, gas-only and parallel mode of solar and combustion over a period of 360h. Even operation during cloudy periods could be covered without problems, producing a smooth and constant electric power output.

The system was successfully operated in all modes, solar-only, combustion-only and parallel mode of solar and combustion over a period of 360h. The system was successfully operated in all modes, solar-only, combustion-only and parallel mode of solar and combustion over a period of 360h. Even operation during cloudy periods could be covered without problems, producing a smooth and constant electric power output. Operation has proven to work well, and emission data are encouraging. NOx emissions can be contained well below 0.5 g/kg fuel, with methane equivalent hydrocarbon emissions between 0.1 and 1 g/kg-fuel. One remaining task is to lower carbon monoxide emissions, which are currently in the range 5-10 g/kg fuel.

The basic element of the solar-hybrid receiver is a sodium heat pipe, using conventional spot welded screen wick structures with arterial webs. The power is introduced either through the solar absorber surface and/or over the gas heat exchanger and is transported to the Stirling heat exchanger tubes by the working fluid of the heat pipe, sodium in this application. At the Stirling heat exchanger there is an equal heat flux distribution, improving efficiency and lifetime of the system. A low-emission, high-efficiency and high-density combustion system for high-temperature applications has been developed, adapted to the hybrid heat pipe receiver. It is a lean premix pre-vaporise combustor using combustion gas recirculation to lower the combustion temperature. To re-circulate combustion gases and to mix air,
Research Areas

A new method for manufacturing heat pipe capillary structures has been developed. Controlled open porous layers for new-type heat pipe capillary structures have been produced with radio-frequency plasma spraying (RF-PS). The RF-PS capillary structures show the possibility of low-cost production of capillary structures, not only for heat pipe applications. Refractory metals as well as ceramics have been sprayed using typical heat pipe materials, e.g. nickel-based alloys. Porosities of up to 80% have been reached with molybdenum and of up to 50% with nickel-based alloys. Two prototype sodium heat pipes have been built and tested successfully. Up to a capillary height of 400mm, heat fluxes of more than 100 W/cm$^2$ could be obtained. With RFPS capillary structures, costs of hybrid heat pipe receivers could be decreased at least in the range of factor 5 to 10.

By using adapted equipment production parameters and powders it became possible to produce controlled open porous capillary layers and structures by means of RF-plasma spraying (RF-PS). The principal suitability of the RF-PS method to produce capillary structures was demonstrated with samples of simple geometry. Porous layers for geometries more relevant to heat pipes have now been developed. The method has a high potential for the automatic production of porous and also dense components at very low costs, provided the design of the product is laid out corresponding to the properties of the manufacturing process.

The industry partners involved in this project intend to commercialise hybrid dish/Stirling systems for decentralised power production in the Sunbelt region. Potential markets are the Mediterranean regions like Morocco, as there are many small communities without any connection to the electricity grid. Substituting diesel engines for electricity production or animal-powered water pumping, the total required power will amount to at least 5 GW. Assuming 5 000 hours (hybrid) operation per year, this will result in a considerable reduction of CO$_2$, 20 million tonnes per year corresponding to 250 - 750 M€ savings in fuel costs. The economic forecast is reliable, based on results from nine existing dish/Stirling units. Operating hours for six parallel running dishes at the Plataforma Solar de Almería have accumulated nearly 30 000 hours. The cost forecast for production of the first 100 systems is 7 000 €/kW, decreasing to 1 600 €/kW for a series of 10 000/year.

Nevertheless, further developments are needed to reduce costs, to improve reliability and performance, and to integrate different non-solar fuel, for example biogas.

INFORMATION

Project HYPHIRE
Reference: JOR3-CT95-0085
Duration: 42 months
Total cost: 1.775.003 €
EC funding: 971.894 €
Status: Completed

Partners:
- Deutsches Zentrum für Luft- und Raumfahrt (DE), Co-ordinator
- INTERSOL (SE)
- CIEMAT (ES)
- SBP (DE)
- IKE (DE)

Contact point:
Dörte Laing
Tel: +49 711 6862 608
Fax: +49 711 6862 747

Project HYPHIRE
Reference: JOR3-CT95-0085
Duration: 42 months
Total cost: 1.775.003 €
EC funding: 971.894 €
Status: Completed

Partners:
- Deutsches Zentrum für Luft- und Raumfahrt (DE), Co-ordinator
- INTERSOL (SE)
- CIEMAT (ES)
- SBP (DE)
- IKE (DE)

Contact point:
Dörte Laing
Tel: +49 711 6862 608
Fax: +49 711 6862 747
Abstract

In many high-temperature industrial processes, an external heat source is used to provide the necessary energy to start and to maintain a chemical reaction. This heat originates either from electricity or from fossil fuel combustion. Concentrated solar thermal systems can replace them as a source of heat making the industrial process cleaner and reducing greenhouse gas emissions. The SOLASYS project investigated the gas reforming process to produce a synthesised-gas usable in a gas turbine.

The objective of the work was to develop and demonstrate a novel high-temperature solar process for a gas reforming system leading to electricity production. The novel process comprises solar upgrading of hydrocarbons by steam reforming in solar specific receiver reactors, and the utilisation of the upgraded fuel in highly efficient conversion systems such as gas turbines or fuel cells. This process can be used at small scale as a stand-alone system for off-grid markets as well as on the large scale to be operated in connection with conventional combined-cycle plants. The solar reforming process has an intrinsic potential for solar/fossil hybrid operation as well as a capability for solar energy storage.

Challenges and Approach

In a previous project, a volumetric receiver reactor was designed to operate in a closed loop to produce synthesised-gas, syngas, from CO₂ reforming of methane. In the project SOLASYS, the major challenge was to modify the previously developed receiver reactor to operate in an open-loop configuration and to adjust the system to work with steam and different hydrocarbon fuels.

The main areas that needed modification were in the catalytic ceramic absorber and in other parts of the system to withstand the higher operating pressures and temperatures of the receiver reactor. The open-loop configuration was chosen to allow the operation of a gas turbine with the syngas produced. The outlet of the receiver reactor would be connected to the inlet of the gas turbine, which would produce electricity for delivery to the grid.

In the project, the best-suited gas turbine was to be modified and connected to the solar reforming system. The modifications would include conversion for a dual-fuel operating system, a new combustion chamber interfacing with the products, and a linking of its control system to the solar system. The project then intended to operate the whole power system in the power range of 100-300 kW, at the solar test facility of the Weizmann Institute of Science in Israel. Investigations would be also made into the use of fuel cells instead of a gas turbine, along with an economic assessment of the technology.

As part of the project, a study was to be done to investigate the possibility of including a fuel cell within the loop to increase the global energy efficiency of the system.

Results

The entire power generation system was completed, commissioned and tested. The project designed a new volumetric receiver reactor, modified a gas turbine and operated a reforming loop. The major technical innovations developed as a result of the work were the modification of the gas turbine, which included dual-fuel operation mode, synthesised-gas and fossil fuel, the adjustment of the control system and operating scheme, the development of the volumetric receiver reactor for which solar specific components such as a quartz window and catalytically active absorbers to bear higher pressures and temperatures were designed, and the operation of the complete solar reforming process using LPG as fossil fuel.

The syngas from the reforming process was sent to storage tanks and the composition was analysed from samples taken from the tanks at one location. The lower heating value of the syngas composition was measured at 21740kJ/kg, 25% higher than the non-reformed fuel. During the solar reforming test period, the solar reformer was operated in the power range 100-150 kW, producing syngas at 7.5 barabs and 720°C, with a conversion rate close to chemical equilibrium. The gas turbine ran smoothly on various mixtures of LPG and syngas up to a 90% syngas fraction. The efficiency of the gas turbine was not affected up to 40% syngas fraction. During operation, special attention needed to be given to start-up and stop modes of the gas turbine operation to avoid stalling problems. For a syngas fraction above 90%, the combustion chamber and piping system will require design modifications to suit the large changes in volumetric flows to improve the gas turbine efficiency.
Based on the system studies, the performance tests and the carbon deposition study, the fuel cell investigation showed that solid oxide fuel cells perform better than molten carbonate fuel cells in terms of application of the solar reformer system. The study concluded that application of fuel cells in the SOLASYS system would give significant energy efficiency benefits. However, the system would then become much more complex and much more expensive.

The driving force for the use and commercial application of concentrated solar power technologies is the environmental issue, i.e. reduction of greenhouse gas emissions. Nevertheless, any new technology including solar reforming would also need to meet the economic criteria for successful market introduction. For a medium-term commercial application of the technology developed, the project identified two approaches. The first option would be the addition of a "solar upgraded fuel" system into existing large-scale gas turbine power plants, which would be attractive for small solar contribution and syngas fraction in the range of 5 to 10% with plant size of 1 to 10 MW. In this case, no major modifications of the gas turbine would be necessary and the financial risk would therefore be reduced. However, subsidies of 5 to 10€cents/kWh would still be needed to make such an option economically attractive. The second option would be to apply the technology of solar reforming in a biogas plant from municipal or agricultural waste installation. In this case, the tipping fee would be in the range of 30-50 €/tonne of biomass and the solar installation would reform the landfill gas.

Nevertheless, additional research is still necessary to complete the project achievements. This includes further operation of the gas turbine in "dual fuel" mode of operation and would require the involvement of gas turbine manufacturers for their knowledge and to gain their approval. It would also need the development of short-term inexpensive syngas storage systems to serve as a buffer between the reformer and the gas turbine.

In the project, the production of electricity with "solar upgraded fuel" was scientifically and technically proven. This comprises reforming of hydrocarbons into energy rich syngas mixtures using a solar driven reformer and combustion in an adapted gas turbine. During the operation period, the feasibility of the volumetric receiver reactor (solar reformer) concept, of dual fuel gas turbine operation and of controlling the solar driven chemical process were successfully demonstrated. This is the first time that a novel solar assisted fuel driven power system had been tested. The consortium has a strong interest in continuing the developments begun in the SOLASYS project in future work, by reinforcing the project team to include utilities, gas companies and local industry at early stages of development to enhance exploitation and dissemination in view of commercialisation of small-scale systems.
High Temperature Solar Thermochemical System: Metal Production

Challenges and Approach

Concentrated solar thermal system is a source of heat and high temperatures above 1,000°C can easily be reached. This makes solar energy an ideal replacement for electricity or fossil fuel usually used to start and to maintain the chemical reaction needed in high-temperature industrial processes, which will make the industrial process cleaner and reduce greenhouse gas emissions.

The project SOLZINC was designed to investigate the technical feasibility of a 0.5 MWth solar thermal chemical reactor for producing metallic zinc from zinc oxide using carbon as a reducing agent. This technology, for a smelting solar-reactor of 500kWth, and the expertise to operate such a reactor do not currently exist, and the state of the art of the technology at the start of the project lay in processes using solar energy at a level of less than a few kWth. The consortium took up the challenge to create new technologies and to develop the know-how to design, manufacture and to operate an innovative new solar reactor.

The key elements in this solar system are the solar reactor, the quench system for the recovery of zinc and the zinc-air fuel cells. The consortium’s approach to tackle the challenges was to divide the project into two phases. During the first phase, several 5-10 kWth versions of the solar reactor were to be built and tested in order to quantify performance variables, such as the specific conversion rate of zinc oxide to zinc as a function of temperature and the type of carbon as a reducing agent, and to qualify the plant concept. The experimental results obtained were then to be used to develop and validate a numerical model to predict performance as a function of operating conditions and to finalise the design concept for a large-scale reactor. The intention in the project was to then choose a reactor design to scale-up to a 0.5 MWth plant.

The second phase would develop the work even further and design, construct and test a larger solar reactor unit. A numerical model would be validated using empirical data from the larger reactor to check the scale-up effects on the simulation. A 10kWth zinc-air fuel cell system, suitable for up scaling for small electric power plants based on zinc dust, would also be designed, built and tested using the powder produced by the plant.

Based on the test results from the prototype plants, a detailed economic study of the technology costs and how economically the solar process mitigates CO₂ emissions and produces electricity via the ZnO-Zn cycle was to be carried out. The experimental, numerical, and eco-efficiency results were then to be used to develop a conceptual design for the reactor and the other components of the ZnO-Zn cycle, paving the way for a demonstration on an industrial scale. Numerous exploitation scenarios for a solar zinc oxide to zinc plant were also to be studied including the option to produce H₂ from zinc by hydrolysis.

The large-scale reactor was to be tested using the 0.5 MWth beam down installation at the Weizmann Institute of Science in Rehovit in Israel with the instrumentation and measurements provided by the French CNRS-IMP Institute. The 5-10 kWth laboratory tests were to be performed in the solar furnace at Paul Scherrer Institute (PSI) in Switzerland and in the solar simulator at the Swiss Federal Institute of Technology (ETH).

The consortium included two industrial partners, which ensured that project maintained an industrial vision. The Swedish ScanArc Plasma Technologies AB has vast experience in zinc-smelting and the treatment of off-gas containing zinc vapour. This partner’s role was to develop the condensing unit to produce zinc-dust with controlled zinc re-
oxidation and particle size and the off-gas treatment equipment. The German zinc/air fuel cell manufacturer, Zoxy Energy Systems GmbH, was instrumental in optimising the cell modules for the requirements of the solar ZnO-Zn cycle, in the development and testing of a 10 kWth zinc-air fuel cell module and in the investigation of the separation of zinc oxide and potassium hydroxide in the spent fuel cells.

The expected long-term benefits of the technology include the following: the mastering of solar energy storage and thermo-chemical transportation, a reduction of CO₂ emissions, a saving of fossil fuel resources, an opportunity for a nearly emission-free urban transport system, and an expansion of employment opportunities in the field of renewable energy.

Progress to date

The first phase of the project has been completed successfully. In typical small solar-reactor tests with 5-6 kWth power input into the reactor, 750 g of a mixture of some 85 mass-% zinc oxide and 15 mass-% charcoal powder are converted primarily into gaseous zinc and carbon monoxide at a reaction temperature of about 1 200°C within 40 minutes.

In the optimisation tests, the key information necessary for the design of the solar pilot reactor in terms of geometrical arrangement, choice of construction material, choice of reducing carbon and of relevant reaction rates at different temperatures was generated. The dependence of the specific zinc-production rate on major process variables like carbon type, temperature, and stoichiometry of the ZnO-C-mixture was investigated in a solar furnace and in a solar simulator. A heat transfer model based on the radiosity exchange method describing the reactor was also developed and a more sophisticated model is now under construction.

The concept for the large reactor evolved in the course of the experimental and numerical work, which lead to the design and construction of a new "two cavity batch reactor", which was successfully tested on the small scale. This reactor has a wall or absorber plate that separates the reactants from the reactor’s window. Based on the results from the process and small-scale reactor tests, an indirectly heated, fixed bed down reactor concept for mixed zinc oxide and carbon was chosen. This was further optimised for 5-10 kWth and then scaled up. A batch process was selected for ease of operation. The reactor was then modified and optimised in several steps. Reactor modelling helped in the process of up scaling to the prototype scale.

The design of the 500kWth prototype solar reactor is now complete, including the planning for all the necessary instrumentation, plant equipment and process control.

A test rig for the development of an effective condensation process of zinc from the off-gas directly into zinc dust has also been realised. Numerous tests for the direct production of dust from the off-gas were also performed at the small scale with an evaluation of the suitability of the dust qualities for use in the zinc-air fuel cells. Zinc-air fuel cells were also successfully operated using anodes from zinc-dust. The design of the off-gas system, including the zinc-dust production unit, was also completed for the prototype plant. Plant components have been ordered, manufactured and delivered to the test facility to be integrated into the concentrated solar thermal system. Completion of the installation is expected by the end of August 2004 with commissioning tests starting later in the year.
Abstract

Hydrogen is foreseen as the fuel of tomorrow. The current standard production routes are either through fossil fuel reforming processes or through electrolysis processes. To date, the most advanced renewable technology capable of producing hydrogen through a non-electrolysis process is based on biomass. The first section of this brochure described concentrated solar thermal technologies as a source of high-temperature heat. As such they are able to produce hydrogen. Laboratory investigations and theoretical studies have shown that concentrated solar energy could indeed be used through thermochemical reactions to produce hydrogen.

The project HYDROSOL investigates a two-step water splitting reaction using a catalyst that would lead to a clean and CO₂-free emission process to produce hydrogen. The first objective is to design, to build and to test a prototype-scale reactor for continuous operation. The second objective is to prove hydrogen generation through a solar process, never done before. The third objective is the assessment of the technical and economical cost and potential, based on experimental data on hydrogen production and actual reactor cost.

A successful outcome will lead to the world’s first continuous production of hydrogen using concentrated solar thermal energy.

High Temperature Solar Thermochemical System: Hydrogen Production

Challenges and Approach

The standard technologies to produce hydrogen are either through fossil fuel reforming processes or through electrolysis processes. However, in view of their higher efficiency and global energy efficiency, non-electrical processes are the preferred option. For renewable energy sources, technologies using biomass as a source are being developed and are nowadays the most advanced renewable technology capable of producing hydrogen through a non-electrolysis process. Concentrated solar thermal technologies are the only other renewable energy source capable of generating the necessary high temperature heat for processes allowing hydrogen production. These technologies have also the advantage of offering several paths for production, like the direct splitting of water molecules or thermochemical reactions. This advantage has the possibility to lead to several competing systems and therefore lower costs.

Because water is the most common element on Earth, the most economically attractive reaction for the production of hydrogen by far is the decomposition of water and direct hydrogen production. However, unfavorable thermodynamic conditions dictate that reasonable hydrogen yields can only be achieved at very high temperatures, above 5 000 K. At this temperature level any concepts trying to use solar energy as the driving energy for the reaction face major technological difficulties, such as finding suitable high-temperature resistant materials.

Another option is to use catalytic materials. Then, the hydrogen production is carried out via a two-step process. In the first step, the activated catalyst dissociates water and produces hydrogen, and in the second step the used catalyst is regenerated. This concept has been proven experimentally, although the catalyst regeneration temperatures are still high, above 1 600°C.

Therefore, at the start of the HYDROSOL project, the state of the art for hydrogen production using concentrated solar thermal energy remained a mainly theoretical investigation, with some very small-scale reactor testing, less than a few kWth, usually tested under simulated solar conditions.

The basic idea behind HYDROSOL was to combine a support structure capable of achieving high temperatures when heated by concentrated solar radiation, with a catalyst system suitable for water dissociation and at the same time suitable for regeneration at these temperatures, so that complete operation of the whole process (water splitting and catalyst regeneration) could be achieved in a single solar energy converter.

For the solar reactor, a 10kWth prototype was to be designed, built and tested under real solar conditions. Hydrogen would be produced and production efficiency and catalyst resistance measured. The regeneration procedure would also be verified.

The project was also designed to investigate the associated coating technology on supports and integration of the developed material technologies into a solar catalytic reactor suitable for incorporation into solar energy concentration systems. A pre-commercial-scale reactor, around 500kWth input power, would be designed and simulated, and...
would include a full generation-regeneration system. Finally, the project would utilise the knowledge gained to assess the real cost of a concentrated solar thermal hydrogen production plant and lay out the necessary steps to bring the cost to a competitive level with standard technologies, opening the way to a complete hydrogen fuel production unit based on solar energy.

The project is structured around four European partners, two industrial and two research institutes, with complementary knowledge, skills and research interaction and strong support from key industrial sectors. Research efforts on advanced material synthesis, advanced ceramics manufacturing and catalytic coatings on porous media can be immediately transferred and coupled with solar technology facilities in order to exploit solar heat for hydrogen production. The industrial partners are involved not only in supplying the know-how for the engineering, manufacture and scale-up of properly "tailored" high-temperature honeycomb-based integrated catalytic systems, but also to ensure the fast commercialisation of the project results and their integration within hydrogen technologies.

Progress to date
After the first 18 months of the project, the results obtained are very encouraging. The preliminary results have demonstrated that the concept, on which the project is based, is feasible.

Catalytic materials have been synthesised via several alternative routes (solid-state synthesis, combustion synthesis and aerosol spray pyrolysis). Under laboratory conditions, these catalysts have been tested for their catalytic activity with respect to water splitting. Water reacts with the solid materials used and produces hydrogen, giving away its oxygen to the solid, at reasonably low temperatures (600-750°C), with hydrogen being the only reaction product in most cases.

A small-scale solar reactor, in the region of 10kWth, has been designed, built and commissioned and solar tests to produce hydrogen are due to start during summer 2004. The preliminary design of a continuous solar reactor has also begun, based upon the results from the catalyst development and coating.

In the second period of the project, activities will focus on solar tests and technology assessments. Nevertheless, continued research efforts on catalyst development will involve screening and comparison among various catalytic materials in order to increase the conversion rate of water to hydrogen and optimise the catalyst regeneration conditions.

The project is due to finish in October 2005. Non-confidential information will be published mainly in scientific and technical journals to attract new partners, especially industrial companies, interested in pushing the developed technology into the market.
SALES AND SUBSCRIPTIONS

Publications for sale produced by the Office for Official Publications of the European Communities are available from our sales agents throughout the world.

**How do I set about obtaining a publication?**

Once you have obtained the list of sales agents, contact the sales agent of your choice and place your order.

**How do I obtain the list of sales agents?**

- Go to the Publications Office website http://publications.eu.int/
- Or apply for a paper copy by fax (352) 2929 42758
This brochure provides an overview and a compilation of research areas in the field of concentrated solar thermal systems. The overview will inform on the current state of the art, development and implementation of concentrated solar thermal technologies in Europe and the world. The research areas defined correspond to a compilation of projects funded under the Thematic Programme “Energy, Environment and Sustainable Development” of the fifth RTD Framework Programme (1999-2002) and previous research Framework Programmes. For each research area, basic information is provided with regard to scientific and technical scope, the participating organisations and contact points.