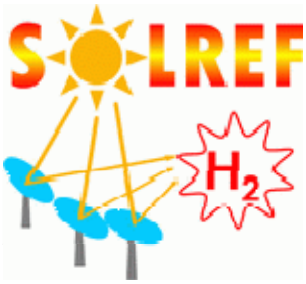

Project no. SES6-CT-2004-502829

SOLREF

Solar Steam Reforming of Methane Rich Gas for Synthesis Gas Production

Publishable Final Activity Report

Period covered:
1 April 2004 – 30 June 2010
Start date of project: 1 April 2004
Project coordinator name:
Editor:
Project coordinator organisation name:
DLR, Cologne

Date of Preparation:
29 July 2010
Duration: 75 months
Dr. Christian Sattler
Dr. Christian Raeder
Version: June 2010

Project Execution

Objectives

The solar reforming process which is carried out in SOLREF enhances the calorific value of CH_4 by 25%, contributed by the solar energy. The synthesis gas produced ($CO+H_2$) can either be used to generate electricity, to provide hydrogen as an energy vector or to produce Fischer Tropsch synthetic fuels. Solar reforming of CH_4 was tested in a 400-kW scale. SOLREF is based on the successful SOLASYS project supported in FP4. A result of this project was that essential modifications are required to advance this unique solar technology to the prototype stage in the 1 MW range. In the beginning a design study for a prototype to be operated at a natural gas well in southern Italy was planned. Due to a change in the consortium this was changed to cover more possible locations in the whole Mediterranean region. The major innovative modification of SOLREF is a new catalytic system for higher operating temperatures which allows a broad range of feed compositions and means to avoid the carbon deposition in the reformer reactor. In addition an advanced solar reformer was developed including basic mechanical and process improvements, like a new front flange, innovative insulation and replacement of the nitrogen purge streams. These modifications were tested and validated under real solar conditions at the Weizmann Institute of Science in Israel. Besides, biogas, landfill gas and contaminated natural gas (CH_4 with a high content of CO_2) can be processed and upgraded, using the SOLREF technology. With this feedstock, reduction of CO_2 emission is significantly enhanced.

Work performed

The work in SOLREF was carried out in five work packages. The following aims were tacled

WP1:

- Investigate various catalyst systems
- Determine the kinetics of the final selected catalyst
- Simulate mass and heat transport and reaction in porous absorber
- Simulation of the transport and reaction in the porous absorber
- Preparation of the solar reformer-scale catalyst-coated segments

Using a wide variety of experimental analysis methods, an appropriate catalyst was selected and coated onto a 3D-foam absorber material. Its thermal durability was partially assessed by experimental methods as a function of temperature. N_2 physi-sorption (BET), CO adsorption (COMA), transmission electron microscopy (TEM) and x-ray diffraction (XRD) were used to characterize the catalysts. Moreover computational models were used to develop a silicon carbide 3D foam as a carrier for the catalyst with excellent thermal properties for this task. Models for the simulation of the heat and mass transfer based on computer tomography generated 3D foams were developed by ETH and are available. The kinetics of the catalyst was determined in an experimental setup and is described in deliverable 1.4.

WP2:

- Develop an advanced advanced 400 kW_{th} solar reformer
- Perform thermodynamic and thermo-chemical analyses to support the system design phase.

Based on the boundary conditions at the Weizmann Institute of Science (WIS), the layout of the absorber was realised. The shape of the absorber was chosen in a way that the angular averaged solar flux density is between 470 kW/m^2 and 700 kW/m^2 on the centre disc and the rings of the main absorber section. To bring SOLREF technology forward to market introduction, a certification process for the pressurised metal components (vessel and flange) was carried out in the Netherlands organised by HyGear and DLR. The final detailed construction is based on the certified vessel and flange.
In parallel a thermo-chemical analysis and a system model of the existing test plant at WIS were realised. A steady state system model for the WIS test plant was implemented and tested. The model can be used to predict the results of changes in the system layout.
For investigating the transient behaviour of the solar reforming plant, a dynamic model of the existing test plant was developed. This model is focusing on the transient behaviour of the solar chemical receiver. This model allows to study the transient behaviour of the reactor during solar operation. It is a tool for implementing reactor controls, optimising start-up and shut-down routines and assessing the influence of design changes on reactor dynamics to substitute the purge gas (N_2) feed. A pressure swing adsorption system was developed and installed. H_2 can now also be used as purge gas feed to reduce cost.

WP3:

- Operate the reformer with gas mixtures which represent the variety of possible feedstock on the solar tower at WIS, Israel, producing partly-solar hydrogen
- Evaluate new operation strategies

The receiver is fully functional and was installed on the solar tower at the Weizmann Institute of Sciences. A test campaign was carried out demonstrating the feasibility of the SOLREF technology. The storage vessel was used for the test with an amount of 2.2 tons liquefied petroleum gas (LPG) (for generating the steam and preparation of the methane).
A battery of 16 cylinders with CO_2 with a pressure of 50 bars and a total weight of 400 Kg, a battery of 42 cylinders with H_2 with a pressure of 200 bars and total volume of 420 Nm^3 and a battery of 24 cylinders with N_2 with a pressure of 200 bars and total volume of 240 Nm^3 were used to run the test campaign.
The catalyst in the pre-reformer was activated. All system checks were performed positively. Minor adjustments were carried out to guarantee a fast start-up from standby status to the hot tests.

WP4:

- Pre-design of a 1 MW_{th} prototype plant in Southern Italy
- Conceptual layout of a commercial 50 MW_{th} reforming plant

Two different cases, 1 MW and 50 MW solar tower concepts, were analysed. For each case two types of reformer were investigated and two possible solutions were analysed. The first solution consists in the reformer integrated type. The second solution is the separated reformer type. The integrated reformer type allows a more compact construction, since the solar receiver has the catalyst on the internal surfaces that permit the reforming process. The separated reformer type allows a wider range of working temperature and a smaller and more compact solar receiver. Assessments on the solar sub components were performed. For the top solutions results for the small 1MW prototype and the 50MW commercial plant are obtained based on cost and optical optimisations. Due to the cost-benefits analysis, the tower top solution with the integrated reformer type was chosen.

WP5:

- Assess on potential markets including cost estimation and environmental, socio-economic, and institutional impacts. Following major results have been achieved during the project:

In order to analyse the markets for a renewable energy technology such as the solar reforming process of methane or LPG, well founded information on demand and resources, technologies and applications is essential. In a detailed analysis carried out by the systems analysis department of DLR showed the possibilities for the application of the technology with a focus of the Middle East and Northern African (MENA) region.
The SOLREF technology has efficiency benefits compared to other technologies for renewable fuel especially hydrogen production, since it allows the production of hydrogen and storage of the produced CO_2 in the same location using only solar energy. Therefore its carbon footprint is much smaller compared to its competitors based on fossil resources. It becomes even smaller if renewable carbon sources are used like biogas.
Based on these results it could be shown that SOLREF is a feasible technology as well for the generation of a partly renewable fuel for the MENA region as for the fuel supply for Europe.
Especially the MENA region shall be in the focus because the population growth will lead to about the same population in the area in the region as in Europe in 2050 with a drastically increased life standard.
It must further be investigated if the expansion of renewables energies would imply unbearable economic constraints on the national economies of the analysed region.

Plan for using and disseminating the knowledge

Section 1 - Exploitable knowledge and its Use

The high temperature catalyst development can be applicable to commercial reforming technology, not necessarily limited to solar. Solar Reforming will be considered not only as a stand alone process. It may be joined with solar gasification of carbonaceous materials for final polishing of the off-gases to produce synthesis gas.
The partners specifically have developed a range of coke resistant, thermally durable catalysts with high solar radiation absorption characteristics for use with concentrated solar radiation. In addition thermally durable coating methodologies tailored to SiC substrates were developed. The project partner Johnson Matthey could support the exploitation of this knowledge through catalyst preparation and substrate coating as soon as a commercial opportunity arises. HyGear has developed a pressure swing adsorption (PSA) for hydrogen purification adapted to the boundary conditions at Weizmann Institute of Science. No patents were prepared in the project.

Tab 1 Exploitable knowledge and its use

Exploitable Knowledge (description)	Exploitable product(s) or measure(s)	Sector(s) of application	Timetable for commercial use	Patents or other IPR protection	Owner & Other Partner involved
high temperature catalyst	Methane/LPG Reforming	Energy Industry	tbd	none yet	The Centre for Research and Technology Hellas, Greece (CERTH)
Thermally durable coatings tailored to SiC substrates	Methane/LPG Reforming	Energy Industry	tbd	none yet	Johnson Matthey
Pressure Swing Adsorption	Methane/LPG Reforming	Energy/Chemical Industry	tbd	none yet	HyGear
Solar Reformer	Methane/LPG Reforming	Energy/Chemical Industry	tbd	none yet	DLR

Section 2 - Dissemination and use

The academic partners in WP 1 have already and plan to continue to disseminate some of the results obtained in the areas of catalysts, kinetic modelling and flow simulation via scientific publications, with the permission of all the other partners.
As in the DoW described, solar reforming plants are an innovative way for the reforming of natural gas. The process is applicable to a large number of industrial sectors where synthesis gas is needed for production of chemicals, not just in the energy sector.

The communication actions are related to

- Presentation of research results.
- Interaction with other European projects.
- Introduction of the technology into the market.
- Planned Actions beyond the project. (E.g. Realisation and the construction of a 1 MW_{th} prototype plant.)
- Continuation of the operation of the SOLREF reactor at CSIRO, Newcastle, Australia

The potential end-users or other interested parties have been provided with information on the new technology and industrial possibilities, stressing the advantages mainly from an industrial and quality point of view. A marketing effort is in progress to export the technology to sites where solar radiation is plentiful and where biogas, landfill gas, and contaminated natural gas are available in the vicinity. The consortium had and continues to disseminate general results in the "concentrated solar power" community and in other communities relevant for the task e.g. IEA SolarPACES and HIA, HyNet, INNOHYP CA, the hydrogen and fuel cell joint technology initiative (FCH-JTI) or specific workshops. Publications in relevant scientific journals and presentations at conferences will be made by all partners who are involved in that task, particularly by the research institutes DLR, APTL, WIS and ETH. The communication strategy also aims to encourage contact with outside parties working in RTD projects on advanced reforming technologies.
Beyond the SOLREF project the next step for the commercialisation of the technology and its exploitation would be the realisation and the construction of a 1 MW_{th} prototype plant. This plant could be built in South Italy. Solar Heat and Power S.p.A. will undertake all the necessary steps required to build such a plant and would be responsible for the manufacturing of the solar components and the integration of the entire plant in conjunction with HyGear.
In the second reporting period a symposium on solar thermal produced hydrogen was organised by DLR. At this international event the SOLREF project was presented. It was outlined the strategic importance of solar steam reforming to go forward to the future renewable hydrogen production.
Furthermore it is planned to cooperate with Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO). The SOLREF reactor, after being revised by DLR staff in Cologne, will be sent to the CSIRO solar energy centre for long term tests.
In addition to the provisions of articles 10, 11 and 12 of the Annex II, General Conditions, the consortium has defined a realistic, coherent and consistent Project Communication Action Plan.
In Tab 2 the actual and planned communication actions are listed. It is an update of the overall list.

Tab 2 Dissemination of results

Planned /actual	Dates	Type	Type of audience	Countries addressed	Size of audience	Partner responsible /involved
planned	2011	Further test, workshops	Research, Industry	Australia, Japan	20	DLR, HyGear
planned	September 2010	Participation at SolarPACES Conference	Research, Industry	All	50	DLR

Planned /actual	Dates	Type	Type of audience	Countries addressed	Size of audience	Partner responsible /involved
actual	September 2009	Participation at SolarPACES Conference	Research, Industry	All	35	DLR
actual	March 2008	Participation at SolarPACES Conferences	Research, Industry	All	20	DLR
actual	Sept 2007	Oral presentation and paper at EAC 2007 (conference)	Research	All		ETH
actual		Paper at the 5th International Symposium	Research	ALL		ETH
actual	2007	Publication in peer-reviewed journal	Research	All		ETH
actual	2007	Publication in peer-reviewed journal	Research	All		ETH
actual	2007 submitted	Publication in peer-reviewed journal	Research	All		ETH
actual	2007 submitted	Publication in peer-reviewed journal	Research	All		ETH
actual	2007 submitted	Publication in peer-reviewed journal	Research	All		ETH

actual	2007	Publication in proceedings	Research	All		ETH
actual	March 2007	Oral presentation and paper at PARTEC 2007 (conference)	Research	All	400	APTL
actual	Feb. 2007	Workshop	Research and stakeholders	Turkey	100	DLR
actual	Nov. 2006	Workshop Final meeting of Innohyp CA	Research and representatives from Brussels	European countries	30	DLR
actual	October 2006	Poster at General Assembly (symposium)	Research and stakeholders	European countries	400	DLR as coordinator
actual	July 2006	Oral presentation and paper at ISEC (conference)	Research	All	400	DLR, HyGear
actual	June 2006	Workshop Maghreb-Europe project	Research and stakeholders	European countries and Algeria	20	DLR
actual	2006	Fact Sheet brochure	Research and public	All		DLR as coordinator
actual	2006	Synopsis brochure	Research and public	All		DLR as coordinator
actual	2006	Expert's workshop	Research	All		WIS
actual	2006	SolarPACES annual report	Research and public	All		DLR

actual	2006	Paper published in Energy&Fuels (peer-reviewed journal)	Research	All		WIS
actual	2005	Paper submitted to Energy (peer-reviewed journal)	Research	All		ETH, DLR
actual	2005	Paper published in Applied Catalysis (peer-reviewed journal)	Research	All		WIS
actual	December 2005	Review Days	Research	European countries	500	DLR
actual	November 2005	Participation at EHEC (conference)	Research	All	300	consortium
actual	October 2005	Poster at IPHE event	Research	All		DLR as coordinator
actual	June 2005	Organization of a symposium	Research and public	All, mainly Germany	100	DLR
actual	June 2005	Oral presentation and paper at ECOS conference	Research	All	500	ETH, DLR
actual	March 2005	International fair	General public	All	10,000	DLR
actual	March 2005	Attending in an event Poster presentation	Actors in the field of Hydrogen	All	400	DLR
actual	January 2005	Media release	General public	German speakers		DLR/WIS

actual	Nov 2004-Jan 2005	Project web-site	General public	All countries with access to www		DLR
actual	Autumn 2004	Brochure of H_2 projects	General public	All		EC; DLR
actual	Autumn 2004	Publication	Research	German speakers		DLR
actual	October 2004	Press release	General public	Greece		APTL
actual	October 13, 2004	Media event	General public	Greece	50	Organised by APTL
actual	June and Oct, 2004	Conference	Research	all	40	DLR