1. Publishable summary

Solar chemical demonstration and
Optimization for
Long-term
Availability of
Renewable
JET fuel

The European Commission started funding the project SOLAR-JET in the 7th Framework Programme in the field of Aeronautics and Air Transport in June 2011, to pave the way for a carbon-neutral path for producing aviation fuel that is compatible with current infrastructure. The goal of SOLAR-JET is to demonstrate at laboratory-scale a process that combines concentrated sunlight with CO_2 and H_2O to produce kerosene by coupling a two-step solar thermochemical cycle, based on non-stoichiometric ceria redox reactions, with the Fischer-Tropsch process. This fuel path is being researched to evaluate its long-term potential to provide a secure, sustainable and scalable supply of renewable aviation fuel.

The SOLAR-JET project is set up to produce the first-ever solar thermochemical kerosene and to evaluate its performance and economical potential by May 2015. The consortium combines competencies and unique infrastructure capabilities of Bauhaus Luftfahrt (Germany), Eidgenössische Technische Hochschule Zürich (Switzerland), Deutsches Zentrum für Luft- und Raumfahrt (Germany), Shell Global Solutions Intl. (Netherlands) and Arttic (France). The purpose of this report is to present the progress achieved up to month 18, the end of November 2012.

The report is structured to show progress in the four technical work packages, i.e.

1. the definitions for the SOLAR-JET research and technology assessment, and the review of the state of the art of relevant technologies,
2. the experimental and theoretical progress around the core device, the solar reactor,
3. the physical and chemical analysis of the produced synthesis gas, and
4. the first insights in performance and economical issues.

The report closes with a brief summary of the potential impact.

1. Technology assessment framework and state-of-the-art review:

An assessment framework has been established for the quantitative and traceable comparison of different technology options and of very different fuel paths, such as solar-thermochemical versus biological pathways. The assessment method is based on the principle of a weighted decision matrix. Firstly, a set of criteria is defined for the comparison: the fuel readiness level, technical compatibility, substitution potential, well-to-wake greenhouse gas emissions, total reserves left, production costs, water footprint, air quality emissions and cycle efficiency.

Then quantitative measures (metrics) were defined, which assign scores for each of the mentioned criteria for all investigated fuel paths. The scores are obtained from the primary performance metrics of the fuel path with respect to each criterion by pre-defined transfer functions which provide traceability in the process. Weighting factors, which adjust the relative importance of the single criteria, reflect different scenarios and priorities for the fuel path being evaluated. It is possible to turn criteria into prerequisites that have to be fulfilled, while a weight of zero omits a criterion in the further analysis.

> ***The assessment framework thus allows the quantitative evaluation of different fuel paths within different scenarios.***

A review of the state-of-the-art of technology shows that most process steps are already implemented in an industrial environment, and that these process steps have been proven to be applicable with respect to efficiency and cost. However, the thermochemical reaction and the CO_2 capture from the atmosphere are in relatively early stages of their development and require further research. These are possible bottlenecks but the largest progress is expected to occur for these two processes.

An expected result is that the final assessment will show the key advantages and disadvantages of the thermochemical fuel path in direct comparison with other renewable fuel path options. Also it will show the potential impact that key developments can have in the relative performances of fuel paths.

2. Synthesis gas production in the prototype reactor:

Syngas, short for synthesis gas, is the generic term for a mixture of carbon monoxide (CO) and hydrogen (H_2). The name comes from the fact that syngas can be used for chemical syntheses of a large variety of products. Syngas production by simultaneous splitting of H_2O and CO_2 via ceria redox reactions has been demonstrated in a high-temperature solar reactor. The H_2:CO molar ratio of the syngas was controlled in a range from 0.25 to 2.34 by adjusting the feedstock H_2O:CO_2 molar ratio from 0.8 to 7.7. Ten consecutive H_2O/CO_2 gas splitting cycles have been performed over 8 hours, yielding a constant and stable syngas composition[1].

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[1] [1] Ph. Furler, J. R. Scheffe and A. Steinfeld, "Syngas production by simultaneous splitting of H_2O and CO_2 via ceria redox reactions in a high-temperature solar reactor", Energy Environ. Sci., 5, pp 6098–6103 (2012), DOI: 10.1039/c1ee02620h

[2] Ph. Furler, J. R. Scheffe, M. Gorbar, L. Moes, U. Vogt, and A. Steinfeld, "Solar Thermochemical CO_2 Splitting Utilizing a Reticulated Porous Ceria Redox System", Energy Fuels, 26 (11), pp 7051–7059 (2012), DOI: 10.1021/ef3013757

[3] J. R. Scheffe and A. Steinfeld "Thermodynamic Analysis of Cerium-Based Oxides for Solar Thermochemical Fuel Production", Energy Fuels, 26 (3), pp 1928–1936 (2012), DOI: 10.1021/ef201875v

The results demonstrate the feasibility of ceria-based redox cycles to produce repetitive and controlled amounts of syngas in a solar reactor.

The produced syngas can be directly further processed to kerosene via the Fischer-Tropsch process and hydroprocessing-type upgrading steps.

A reticulated porous ceramic (RPC) structure made of pure CeO_2 was manufactured and tested for CO_2 splitting in the solar reactor prototype [2,3].[1] The solar-to-fuel energy conversion efficiency, defined as the ratio of the calorific value of CO (fuel) produced to the solar radiative energy input through the reactor's aperture and the energy penalty for using inert gas was 1.73% averaged over the whole cycle.

The demonstrated efficiency is roughly four times greater than the next highest reported value to date for a solar-driven device.

Additionally the fuel (CO) yield per cycle was increased by nearly 17 times compared to that obtained with optically thick ceria felt because of deeper penetration and volumetric absorption of high-flux solar irradiation.

3. Synthesis gas analysis:

The syngas analysis is a first important step towards qualifying the solar reactor products for further processing. In the actual chemical synthesis step for long-chain hydrocarbon production from syngas, the heart of the process is the reaction of carbon monoxide and hydrogen over a cobalt-based catalyst system to form long-chain paraffins. In a second process step the long, waxy chains are cracked back to a shorter and more branched product, which is separated into the desired boiling ranges by distillation to extract the synthetic paraffinic kerosene. The key issue is that the cobalt catalysts are very sensitive for operating conditions and presence of contaminants in the feed. For example sub-ppm levels of sulphur will kill the catalyst activity effectively. Clearly this is unwanted.

For this reason the gaseous samples obtained from the ETH solar reactor, containing hydrogen, carbon monoxide and a mixture thereof, were stored for analysis and further processing, which is the achievement of the first project milestone. The stored gases were analysed by the most sensitive method available to the consortium: proton transfer reaction – time of flight – mass spectrometry. A whole string of contaminants were identified (ammonia, organic molecules of different nature, siloxanes) but no traces of sulphur were observed. Concentrations of the contaminants were low enough not to be a concern at the moment.

However, before starting any testing, the gaseous feed should be analysed in detail.

4. Performance potentials and economical perspectives:

As the analyses of impacts and perspectives are inherently downstream tasks, e.g., with respect to the analysis of the technological potential, the preparation of the integration of experimental and theoretical results and the identification of performance improvements have recently begun.

An economic model is under development to analyse key cost drivers of a SOLAR-JET plant and to calculate variable and fixed costs . Elements of costs, as well as material flows, are adopted from economic analyses of similar technical approaches like the ferrite cycle to produce hydrogen or the Fischer-Tropsch process to produce jet fuel from natural gas.

> ***In a first analysis the heliostat field, solar power towers and occasionally the cycle time have been identified as key cost drivers, whereas the cost of the reactant material ceria is not, unlike the case for ferrite in the ferrite cycle. However, the performance of the ceria and reactor is a cost driver as it has a major impact on the overall efficiency, and therefore on the yield of the process.***

The first steps towards modeling of the fuel cost have been completed, and final kerosene fuel costs roughly in the range from 1 to 4 €/l have been estimated, depending on assumptions of efficiency, heliostat field cost, etc.

Project management and dissemination of results:

At the project start, the infrastructure to manage the project was set up (governing boards, in particular General Assembly; internal website including project repository, etc.), and tools and indicators were developed and adapted to the project context and needs. These enabled the continuous monitoring of project progress against contractual obligations. Furthermore, General Assembly meetings (physical meetings and telephone / web conferences) were organized.

As the basis for all dissemination activities, the SOLAR-JET logo and graphical design were created. A public website was designed and set up, which is not yet on-line as the consortium agreed in accordance with the EC that the website will go on-line when the full process chain has been successfully demonstrated within SOLAR-JET. Furthermore, key research results have been published in the journals “Energy & Environmental Science” and “Energy & Fuels”.[1]

Expected results, socio-economic impact and wider societal implications of the project:

It is expected that the experience gained with the existing reactor and with computational fluid dynamic modeling will serve to create an enhanced solar reactor design and to evaluate the potential of the process for scaled-up operations to an industrial level.

The synthesis of the theoretical and experimental results, combined with an overall fuel production path analysis, will provide information on the technological and economic potential of the ceria cycle and the solar fuel production chain that need to be addressed to make full use of this technology potential. The evaluation in the comprehensive assessment framework will show the inherent advantages and disadvantages of the thermochemical ceria cycle as compared to other renewable alternative fuel paths.

At this point in time it is too early to give an accurate assessment of the potential socio-economic impact. A major step for SOLAR-JET to become an integral component in the development of renewable energy for aviation within the EU is the production of “real” kerosene and the establishment of the link to the European aviation industry via the Industrial Advisory Board. Both activities are being given high priority.

The project has the potential to contribute to future carbon-neutral aviation, either through the process demonstrated by SOLAR-JET or through the scientific and technological advancements generated that may open new and better perspectives. Countries in Southern Europe with large amounts of annual direct solar irradiation might then benefit from an influx of investment and revival of their economies.

Here below is the list of the SOLAR-JET Project Partners:

Project consortium			
Project acronym	SOLAR-JET	**Project nr.**	285098
Project scientific coordinator		Dr. Andreas Sizmann	
Beneficiary nr.	**Organization Short Name**	**Address**	**Stakeholders**
1	BHL	**Bauhaus Luftfahrt e.V. (BHL)** Lyonel-Feininger-Str. 28 D-80807 Munich, Germany	Dr. Andreas Sizmann Prof. Dr. Mirko Hornung Christoph Falter Christoph Jeßberger Dr. Valentin Batteiger Oliver Boegler
2	ETH	**ETH Zurich (ETH)** Institute of Energy Technology Sonneggstr. 3 CH-8092 Zurich, Switzerland	Prof. Dr. Aldo Steinfeld Philipp Furler Dr. Jonathan Scheffe
3	DLR	**Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center) (DLR)** Institute of Combustion Technology Pfaffenwaldring 38-40	Dr. Patrick Le Clercq
4	SHELL	Solar Fuels team at **Shell** in Amsterdam Shell Global Solutions International BV Grasweg 31, 1031 HW Amsterdam, The Netherlands	Donald Reinalda
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		General Manager – Global Commercial Technology **Shell** Global Solutions US Inc. Shell Technology Center Houston TX United- States	Paul Bogers
5	ART	**ARTTIC** Elsenheimerstr. 59 80687 München Germany	Dr. Martin Dietz Justine Curtit